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August 2005

Features, Events, and Processes in SZ Flow and Transport

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BSC	SCIENTIFIC ANALYSIS SIGNATURE PAGE/ CHANGE HISTORY	Page iii
		1. Total Pages: ~~203~~ 202 8/20/05

2. Scientific Analysis Title

Features, Events, and Processes in SZ Flow and Transport

3. DI (including Revision Number)

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9. Remarks: Kathy Economy has contributed to the revision of this AMR. She was the author for REV 02 and REV 03 of this document. SC Khamamkar contributed as the DIRS Checker.

Change History

10. Revision No.	11. Description of Change
REV 00	Initial Issue
REV 01	Revision to add 2 new secondary SZ FEPs, address comments by Winston and Strawn, update the text to describe the results of other FEPs and change the format of section 6.2 to include the numbers for secondary FEPs, standardize callouts to include the document identifier, add subheadings and sections to address: related primary FEPs, summary of screening argument, TSPA disposition and supplemental discussion (full screening argument for lengthy evaluations) and related NRC IRSRs.
REV 02	Provide updated SZ FEP screening in alignment with the FEP list modifications given in the TSPA LA FEP list. Provide updated SZ FEP screening to reflect current project knowledge of SZ issues documented in updated SZ AMRs. Resolve TBVs: (1) Resolution of TBV-4924 is documented in Section 6.2.10, (2) Resolution of TBV-4933 (initiated by REV 01 of this document) is resolved in Section 6.2.46. There are no TERS or CIRS affiliated with this AMR.
REV 03	Revision to incorporate Repository Integration Team evaluation comments, to better provide transparency and traceability, revise citations to reflect most current documentation, and comply with revisions of procedures. Changes to REV 03 are too extensive to be indicated by change bars. The entire report was revised; change bars are not used because the changes were too extensive to use Step 5.6(e)(1) per AP-SIII.9Q, REV 01, ICN 07.
Rev 04	Revision to incorporate the conclusions from the white paper entitled: *Impacts of Solubility and Other Geochemical Processes on Radionuclide Retardation in the Natural System* [DIRS 174958] and to address CR 5600. Changes to address peak temperature at the water table. Changes are too extensive for change bars. SPK 8-20-2005

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ACRONYMS AND ABBREVIATIONS

atm	atmosphere
BTC	breakthrough curve
CORAL	colloid retardation factor in the alluvium
CORVO	colloid retardation factor in volcanic units
CSNF	commercial spent nuclear fuel
DOE	U. S. Department of Energy
DTN	data tracking number
EBS	engineered barrier system
ECRB	Enhanced Characterization of the Repository Block
EPA	U.S. Environmental Protection Agency
FEP	feature, event, and process
FISVO	flowing interval spacing in the volcanic units
FPVO	flowing interval porosity
GWSPD	scaling parameter for groundwater specific discharge
HAVO	horizontal anisotropy in the volcanic units
ka	thousand years ago
LA	license application
LDISP	Longitudinal Dispersivity
Ma	million years ago
NAP	National Academic Press
NRC	U.S. Nuclear Regulatory Commission
OQA	Office of Quality Assurance
PRD	*Project Requirements Document*
PSHA	Probabilistic Seismic Hazard Analysis
RMEI	reasonably maximally exposed individual
sv	settling velocity
SZ	saturated zone
TSPA	total system performance assessment
UZ	unsaturated zone

ACRONYMS AND ABBREVIATIONS (Continued)

YMP	Yucca Mountain Project
YMRP	Yucca Mountain Review Plan, Final Report

1. PURPOSE

This analysis report evaluates and documents the inclusion or exclusion of the saturated zone (SZ) features, events, and processes (FEPs) with respect to modeling used to support the total system performance assessment (TSPA) for license application (LA) of a nuclear waste repository at Yucca Mountain, Nevada.

A screening decision, either *Included* or *Excluded,* is given for each FEP along with the technical basis for the decision. This information is required by the U.S. Nuclear Regulatory Commission (NRC) at 10 CFR 63.11(d), (e), (f) [DIRS 173273].

This scientific report focuses on FEP analysis of flow and transport issues relevant to the SZ (e.g., fracture flow in volcanic units, anisotropy, radionuclide transport on colloids, etc.) to be considered in the TSPA model for the LA. For included FEPs, this analysis summarizes the implementation of the FEP in TSPA-LA (i.e., how the FEP is included). For excluded FEPs, this analysis provides the technical basis for exclusion from TSPA-LA (i.e., why the FEP is excluded).

1.1 PLANNING AND DOCUMENTATION

This scientific report is governed by *Technical Work Plan for: Saturated Zone Flow and Transport Modeling* (BSC 2005 [DIRS 173859]).

1.2 SCOPE

The scope of this report is to describe, evaluate, and document screening decisions and technical bases for the SZ FEPs for the TSPA-LA. A TSPA-LA disposition is provided for FEPs included in the TSPA-LA; the disposition is a consolidated summary of how the FEP has been included and addressed in the TSPA-LA model, based on supporting analysis and model reports that describe the inclusion of the FEP. The report also provides a list, or reference roadmap, of the specific supporting technical reports that provide more detailed discussions of the FEP.

For FEPs that are excluded from the TSPA-LA, a screening argument identifies the basis for the exclusion decision (i.e., low probability, low consequence, or by regulation) and discusses the technical basis that supports that decision. The report also provides appropriate references to Project and non-Project information that supports the exclusion.

In cases where a FEP covers multiple technical areas and is shared with other FEP reports, only a partial technical basis for the screening decision as it relates to SZ concerns is provided. The full technical basis for these shared FEPs is addressed, collectively, by all of the sharing FEP reports. This information is provided in Section 6.2 and subsequent sections.

An overview of the Yucca Mountain Project (YMP) FEP analysis and scenario development process is available in *The Development of the Total System Performance Assessment-License Application Features, Events, and Processes* (BSC 2005 [DIRS 173800], Sections 2.4, 3, and 4), describing the TSPA-LA FEP identification and screening process. As part of that process, the TSPA-LA FEP list (DTN: MO0501SEPFEPLA.001 [DIRS 172601]) was developed. This data tracking number (DTN) was used as an input to the SZ FEP analysis. The list of SZ TSPA-LA FEPs (Table 1.2-1) was derived from DTN: MO0501SEPFEPLA.001 [DIRS 172601]. Table 1.2-1 also includes the designation of shared FEPs.

Direct inputs supporting the screening decisions are listed in Section 4. The individual FEP discussions providing identification (FEP number, name, and description) and screening (screening decision, screening argument or TSPA disposition) information are in Section 6.2.

Table 1.2-1. SZ FEPs for the TSPA-LA

FEP Number	FEP Name	Section Discussed in This Document	FEP Shared with Other Disciplines
1.2.02.01.0A	Fractures	6.2.1	UZ
1.2.02.02.0A	Faults	6.2.2	UZ
1.2.04.02.0A	Igneous activity changes rock properties	6.2.3	DE UZ
1.2.04.07.0B	Ash redistribution in groundwater	6.2.4	N/A
1.2.06.00.0A	Hydrothermal activity	6.2.5	UZ
1.2.09.02.0A	Large-scale dissolution	6.2.6	UZ
1.2.10.01.0A	Hydrologic response to seismic activity	6.2.7	DE UZ
1.2.10.02.0A	Hydrologic response to igneous activity	6.2.8	DE UZ
1.3.07.01.0A	Water table decline	6.2.9	UZ
1.3.07.02.0A	Water table rise affects SZ	6.2.10	Bio
1.4.07.01.0A	Water management activities	6.2.11	Bio
1.4.07.02.0A	Wells	6.2.12	Bio
1.4.07.03.0A	Recycling of accumulated radionuclides from soils to groundwater	6.2.46	N/A
2.1.09.21.0B	Transport of particles larger than colloids in the SZ	6.2.13	N/A
2.2.03.01.0A	Stratigraphy	6.2.14	UZ
2.2.03.02.0A	Rock properties of host rock and other units	6.2.15	UZ
2.2.06.01.0A	Seismic activity changes porosity and permeability of rock	6.2.16	DE UZ
2.2.06.02.0A	Seismic activity changes porosity and permeability of faults	6.2.17	DE UZ
2.2.06.02.0B	Seismic activity changes porosity and permeability of fractures	6.2.18	DE UZ

Table 1.2-1.SZ FEPs for the TSPA-LA (Continued)

FEP Number	FEP Name	Section Discussed in This Document	FEP Shared with Other Disciplines
2.2.07.12.0A	Saturated groundwater flow in the geosphere	6.2.19	N/A
2.2.07.13.0A	Water-conducting features in the SZ	6.2.20	N/A
2.2.07.14.0A	Chemically-induced density effects on groundwater flow	6.2.21	N/A
2.2.07.15.0A	Advection and dispersion in the SZ	6.2.22	N/A
2.2.07.16.0A	Dilution of radionuclides in groundwater	6.2.23	N/A
2.2.07.17.0A	Diffusion in the SZ	6.2.24	N/A
2.2.08.01.0A	Chemical characteristics of groundwater in the SZ	6.2.25	Bio
2.2.08.03.0A	Geochemical interactions and evolution in the SZ	6.2.26	N/A
2.2.08.06.0A	Complexation in the SZ	6.2.27	N/A
2.2.08.07.0A	Radionuclide solubility limits in the SZ	6.2.28	N/A
2.2.08.08.0A	Matrix diffusion in the SZ	6.2.29	N/A
2.2.08.09.0A	Sorption in the SZ	6.2.30	N/A
2.2.08.10.0A	Colloidal transport in the SZ	6.2.31	N/A
2.2.08.11.0A	Groundwater discharge to surface within the reference biosphere	6.2.32	Bio
2.2.09.01.0A	Microbial activity in the SZ	6.2.33	N/A
2.2.10.02.0A	Thermal convection cell develops in SZ	6.2.34	N/A
2.2.10.03.0A	Natural geothermal effects on flow in the SZ	6.2.35	N/A
2.2.10.04.0A	Thermo-mechanical stresses alter characteristics of fractures near repository	6.2.36	UZ
2.2.10.04.0B	Thermo-mechanical stresses alter characteristics of faults near repository	6.2.37	UZ
2.2.10.05.0A	Thermo-mechanical stresses alter characteristics of rocks above and below the repository	6.2.38	UZ
2.2.10.08.0A	Thermo-chemical alteration in the SZ (solubility, speciation, phase changes, precipitation/dissolution)	6.2.39	N/A
2.2.10.13.0A	Repository-induced thermal effects on flow in the SZ	6.2.40	N/A
2.2.11.01.0A	Gas effects in the SZ	6.2.41	N/A
2.2.12.00.0B	Undetected features in the SZ	6.2.42	N/A
2.3.11.04.0A	Groundwater discharge to surface outside the reference biosphere	6.2.43	Bio
3.1.01.01.0A	Radioactive decay and ingrowth	6.2.44	Bio UZ WF
3.2.07.01.0A	Isotopic dilution	6.2.45	N/A

Bio = biosphere; DE = disruptive event; FEP = feature, event, and process; N/A = not applicable; SZ=saturated zone; UZ = unsaturated zone; WF = waste form

1.3 SCIENTIFIC ANALYSIS LIMITATIONS AND USE

The intended use of this report is to provide FEP screening information for a Project-specific FEP database, to promote traceability and transparency for included and excluded SZ FEPs, and to document inclusion or exclusion of SZ FEPs within or from the TSPA-LA model. The following limitations apply:

- Because other reports and controlled documents are cited as direct input, the limitations inherently include any limitations or constraints described in the cited reports or controlled documents.

- In cases where FEPs are shared, the scope of this report is limited to the SZ. The full technical basis for the shared FEPs is addressed, collectively, by all of the sharing FEP reports.

- For screening purposes, mean values of probabilities, mean amplitude of events, or mean value of consequences (e.g., mean time to waste package degradation) are used as a basis for reaching a decision to include or exclude. Mean values are determined based on the range and distribution of possible values.

- The results of the FEP screening are specific to the repository design and processes for YMP available at the time of the TSPA-LA. Changes in direct inputs listed in Section 4.1, in baseline conditions used for this evaluation, or in other subsurface conditions will need to be evaluated to determine whether the changes are within the limits stated in the FEP evaluations. Engineering and design changes are subject to evaluation to determine whether there are any adverse impacts to safety, as codified at 10 CFR 63.73 and in Subparts F and G [DIRS 173273]. See also the requirements at 10 CFR 63.44.

2. QUALITY ASSURANCE

Development of this report and supporting analyses are subject to the U.S. Department of Energy (DOE) Office of Civilian Radioactive Waste Management quality assurance program as indicated in *Technical Work Plan For: Saturated Zone Flow and Transport Modeling* (BSC 2005 [DIRS 173859], Section 8.1). Approved quality assurance procedures identified in Section 4.1 of the technical work plan have been used to conduct and document the activities described in this report. The documentation has been prepared according to LP-SIII.9Q-BSC, *Scientific Analyses*, and in accordance with related procedures and guidance documents as outlined in the technical work plan. Section 8.4 of the plan identifies applicable controls for the electronic management of data during the analysis and documentation activities.

The report contributes to the analysis and modeling used to support performance assessment. The SZ FEPs involve the investigations of items or barriers on the *Q-List* (BSC 2005 [DIRS 171190]) and have the potential to affect the calculation of the performance of the natural barriers included on the *Q-List*. However, the SZ FEPs themselves do not qualify as *Q-List* items. The evaluations and conclusions do not directly impact engineered features important to safety, as defined in AP-2.22Q, *Classification Analyses and Maintenance of the Q-List.*

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3. USE OF SOFTWARE

The computer software code used directly in this analysis report is FLAC3D (STN: 10502-2.1-00, BSC 2002 [DIRS 161947]). The operating system and platform is Windows 2000 and was run on a personal computer in Las Vegas, Nevada. FLAC3D was used to estimate the potential changes in temperature and thermally induced stress at the water table due to the repository emplacement. The qualification status of the software is noted in the Software Configuration Management database. The software was obtained from Software Configuration Management and is appropriate for the application, considering the simulation capabilities of the software, the range of inputs, and the functionality required by the computational task. FLAC3D was used within the range that the code was verified.

Commercially available software, which is exempt from Yucca Mountain qualification procedures, was also used. Microsoft Excel 97 Software Release-1 is a commercial software package used to display the data visually using only standard, built-in mathematical functions. Except for plotting and visualization, no routines or macros were developed using this commercial software. The values used and displayed are approximate in nature and are used only to identify a range of expected values. Microsoft Word 2000 is a commercial software package used for word processing and is exempt from qualification requirements, in accordance with LP-SI.11Q-BSC, *Software Management*.

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4. INPUTS

LP-3.15Q-BSC, *Managing Technical Product Inputs*, categorizes technical product input usage as either direct or indirect. A direct input is used to develop the results or conclusions in a technical product. An indirect input is used to provide additional information that is not used in the development of results or conclusions.

Section 4.1 identifies the direct and indirect inputs used in this FEP report. The direct inputs were obtained from controlled source documents and other appropriate sources in accordance with the controlling procedure LP-3.15Q-BSC. Section 4.2 identifies the FEP screening criteria described in 10 CFR Part 63 [DIRS 173273], along with the regulatory derived FEP screening criteria. Section 4.3 discusses codes, standards, and regulations.

4.1 DIRECT INPUTS

The LA FEP list (DTN: MO0501SEPFEPLA.001[DIRS 172601]) was used to provide the list of SZ FEPs for screening in this report. The LA FEP list identifies a FEP report or a set of sharing FEP reports for each FEP. Indirect and direct inputs were used for the FEP screening analysis. Table 4.1-1 indicates the direct inputs used to develop the excluded FEPs. The direct inputs are appropriate for use, as discussed below:

- Established facts:
  - Eckerman and Ryman (1993 [DIRS 107684], Table A-1) present half-life values for selected radioisotopes. The half-life value, which is constant for any particular isotope, is the time required for one-half the atoms initially present to disintegrate.
  - Viswanath and Natarajan (1989 [DIRS 129867], p. 715) present the viscosity of water value. This is a published engineering handbook containing viscosity tables relating to liquids.
  - Streeter and Wylie (1979 [DIRS 145287], p. 534) present the density of water value. This is a published engineering handbook containing data relating to fluid mechanics.
  - Dean (1992 [DIRS 100722] present the density of water value. This is a published handbook of chemistry.
  - 10 CFR Part 63 [DIRS 173273] By specifying characteristics, concepts, and definitions, the regulations serve as de facto inputs used for screening FEPs. The regulatory definitions and elucidation of the regulatory concepts pertaining to the reference biosphere, geologic setting, reasonably maximally exposed individual (RMEI), and human intrusion are explained in detail in Section 4.1.3 of *The Development of the Total System Performance Assessment-License Application Features, Events, and Processes* (BSC 2005 [DIRS 173800]). For the SZ FEPs, the inputs of particular interest include the reference biosphere, the geologic setting, and the RMEI. Specific direct inputs from the regulations addressing these concepts are listed in Table 4.1-2.

- **Site characterization information:**

  Information on site characterization boreholes is provided in inputs DTN: GS010308312322.003 [DIRS 154734], Table S01053 003) and DTN: GS010908312332.002 [DIRS 163555]. Information on site characterization regarding the number of waste packages intersected by a single volcanic event is provided in DTN: MO0504MWDNUMWP.001 [DIRS 173521]. Information on site characterization on the dose conversion factors for selected radionuclides is provided in DTN: MO0501MWDBDCFS.000 [DIRS 172835]. DTN: LA0407DK831811.001 [DIRS 170768] provides the dimensions of basaltic dikes near Yucca Mountain. This is the best available information pertaining to these topics for the site characterization evaluated in Sections 6.2.3, 6.2.4, 6.2.33, and 6.2.41.

- **Data qualified within this report:**

  Unqualified data used as direct input for this report are qualified in Appendix A, where their appropriateness for the intended purpose is documented.

- **All remaining direct inputs:**

  All remaining direct inputs are from model and analysis reports qualified for use to support the Yucca Mountain LA. The information used as inputs from these reports pertains directly to the exclusion arguments in Section 6.2 and, therefore, are suitable for their intended use.

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Table 4.1-1. Input for Excluded SZ FEPs

DIRS	Input	Source	Direct Use In	Description
DIRS 100088	Szabo, B.J. et al. 1994. “Paleoclimatic Inferences from a 120,000-Yr Calcite Record of Water-Table Fluctuation in Browns Room of Devils Hole, Nevada.” *Quaternary Research, 41,* (1), 59-69. New York, New York: Academic Press. TIC: 234642.	Section 3, Figure 6	Section 6.2.9 Appendix A, Section A2.1	(1) Past-climate fluctuations are cyclical and are propagated through UZ to SZ. (2) Calcite crystal formation a function of degree of saturation. (3) Evidence of past water table elevations is seen in crystal morphology and growth in Browns Room. (4) Crystal morphology in Browns Room indicates water table dropped by at least 6 m between 53,000 and 92,000 years ago. (5) Current climate represents an extremely arid condition.
Justification–Analysis of global climate cycles and their impact on basin and range mineral deposits in the Basin and Range Province. Peer reviewed journal				
DIRS 100569	Domenico, P.A. and Schwartz, F.W. 1990. *Physical and Chemical Hydrogeology*. New York, New York: John Wiley & Sons. TIC: 234782.	Chapter 14 Equation 14.11, Chapter 3, Equation 3.23, Chapter 10, Equation 10.2, Chapter 16, Equation 16.2, Chapter 9, Eq. 9.33	Section 6.2.4, 6.2.13, and Appendix C	Equation for radioactive decay, equation for Darcy’s law, advective velocity equation, Darcy’s equation written in terms of pressure gradients and permeability, onset of free convection equation.
Justification–Widely used textbook for geochemistry and hydrology written by experts in their field.				
DIRS 101173	Freeze, R.A. and Cherry, J.A. 1979. *Groundwater*. Englewood Cliffs, New Jersey: Prentice-Hall. TIC: 217571.	pp. 106, 404	Sections 6.2.6 and 6.2.4	(1) Carbonate and halite solubilities, volcanic rocks tend to weather to clay minerals with a relatively small amount of silica going into solution; (2) equation for retardation factor.
Justification–Widely used textbook for geochemistry and hydrology written by experts in their field.				
DIRS 168699	GS010908312332.003. Vertical Head Differences from Water-Level Data Analysis for the Saturated Zone Site-Scale Flow and Transport Model. Submittal date: 10/20/2001.	Table S02261 001	Section 6.2.13	Head differences between NC-EWDP-19D and NC-EWDP-19P
Justification: Nye County Early Drilling Program head differences in the alluvium for wells NC-EWDP-19D and NC-EWDP-19P				

Table 4.1-1. Input for Excluded SZ FEPs (Continued)

DIRS	Input	Source	Direct Use In	Description
DIRS 108074	Cember, H. 1983. *Introduction to Health Physics.* 2nd Edition. New York, New York: Pergamon Press. TIC: 204863.	pp71-74	6.2.4	Reference to the conversion of radionuclide masses to corresponding activities.
Justification	Justification–Widely used textbook for health physics written by experts in their field.			
DIRS 101134	Hillel, D. 1980. *Fundamentals of Soil Physics.* New York, New York: Academic Press. TIC: 215655	Chapter 4, F	6.2.13	Reference to Stoke's Law
Justification	Justification–Widely used textbook for soil physics written by experts in their field.			
DIRS 172601	MO0501SEPFEPLA.001. LA FEP List and Screening. Submittal date: 01/17/2005	Table S05025 001	Section 4.1	LA FEP database
Justification–LA FEP list used to screen FEPs				
DIRS 103731	CRWMS M&O 1998. *Probabilistic Seismic Hazard Analyses for Fault Displacement and Vibratory Ground Motion at Yucca Mountain, Nevada*. Milestone SP32IM3, September 23, 1998. Three volumes. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19981207.0393.	Figure 8-3	Sections 6.2.7, 6.2.16, 6.2.17, and 6.2.18	Probability and degree of displacement for the Solitario Canyon Fault.
		Figures 8-17 through 8-27 and Figures 8-4 through 8-12	Sections 6.2.7, 6.2.16, 6.2.17, and 6.2.18	Mean fault displacements and probabilities for the majority of the faults, representative faults, and block-bounding faults.
		Section 8.2.1	Sections 6.2.7, 6.2.16, 6.2.18 and 6.2.17	Intact host rock mean displacement is less than 0.1 cm for a 1 x 10^{-8} annual exceedance probability between Solitario Canyon and the Ghost Dance Faults and within the repository's elevation.
		Figure 8-2	Sections 6.2.7, 6.2.16, 6.2.17, and 6.2.18	Probability and degree of displacement for the Bow Ridge Fault.
Justification–Documentation of expert elicitation of fault displacement and seismic activity within the Yucca Mountain vicinity.				

Table 4.1-1. Input for Excluded SZ FEPs (Continued)

DIRS	Input	Source	Direct Use In	Description
DIRS 105162	National Research Council 1992. *Ground Water at Yucca Mountain, How High Can It Rise? Final Report of the Panel on Coupled Hydrologic/Tectonic/Hydrothermal Systems at Yucca Mountain*. Washington, D.C.: National Academy Press. TIC: 204931.	Chapters 2 and 5, p. 7, Section 3, Appendix A, Section A2.5,	Sections 6.2.7, 6.2.16, 6.2.17, 6.2.18	(1) Within the Basin and Range Province (which includes the Yucca Mountain region) peak extension stresses occurred between 10 and 12 Ma with extension rates between 10 to 30 mm/year. (2) These rapid extension rates formed two major north-trending extension belts and normal faulting zones. (3) Approximately 5 Ma, regional extensional stress declined to 5 to10 mm/year and are in a declining state today. (1) Predicted rise in water table given future seismic events. (2) Numerical results using a seismic dislocation model indicate the maximum rise in the water table would be approximately 10 m. (3) Results from the regional stress model approach indicated a maximum water table rise of 50 m. (4) Predicted seismic events within the Yucca Mountain region over the next 10,000 years will not alter the large and globally extensive stresses imposed in the rock and in effect over the past 10 to15 million years.
Justification–An analysis to the effects a seismic event would have on water table performed by experts in the field.				
DIRS 107684	Eckerman, K.F. and Ryman, J.C. 1993. *External Exposure to Radionuclides in Air, Water, and Soil, Exposure-to-Dose Coefficients for General Application, Based on the 1987 Federal Radiation Protection Guidance.* EPA 402-R-93-081. Federal Guidance Report No. 12. Washington, D.C.: U.S. Environmental Protection Agency, Office of Radiation and Indoor Air. TIC: 225472.	Table A-1	Section 6.2.4, Table 6.2-1	Radionuclide half-lives.
Justification–Radionuclide half-lives needed for the analysis.				
DIRS 109148	Paces, J.B.; Whelan, J.F.; Forester, R.M.; Bradbury, J.P.; Marshall, B.D.; and Mahan, S.A. 1997. *Summary of Discharge Deposits in the Amargosa Valley.* Milestone SPC333M4. Denver, Colorado: U.S. Geological Survey. ACC: MOL.19981104.0151.	Section 3	Section 6.2.32	Analyzes age, isotope, and paleontological data and summarizes the current understanding and implications of paleo-spring deposits.
Justification–Isotopic, mineralogical, and paleontological study for water levels over several millennia within the Yucca Mountain region.				
DIRS 129867	Viswanath, D.S. and Natarajan, G. 1989. *Data Book on the Viscosity of Liquids*. 714-715. New York, New York: Hemisphere Publishing Corporation. TIC: 247513.	p. 715	Section 6.2.13	Viscosity of water value.

Table 4.1-1. Input for Excluded SZ FEPs (Continued)

DIRS	Input	Source	Direct Use In	Description
Justification–Widely cited handbook quoted giving properties of liquids under various conditions.				
DIRS 145287	Streeter, V.L. and Wylie, E.B. 1979. *Fluid Mechanics*, 7th Edition. New York, New York: McGraw-Hill. TIC: 4819.	p. 534	Section 6.2.13	Density of water value.
Justification–Widely cited textbook giving properties of liquid and solids.				
DIRS 154734	GS010308312322.003. Field, Chemical and Isotopic Data from Wells in Yucca Mountain Area, Nye County, Nevada, Collected Between 12/11/98 and 11/15/99. Submittal date: 03/29/2000.	Table S01053 003	Sections 6.2.33 and 6.2.41	Little to no organic carbon in these well waters.
Justification–Water chemistry analysis used to determine geochemical evolution and current geochemistry of in situ groundwater within the Yucca Mountain vicinity.				
DIRS 155270	DTN: GS000808312312.007. Ground-Water Altitudes from Manual Depth-to-Water Measurements at Various Boreholes November 1998 through December 1999. Submittal date: 08/21/2000.	Table S0039 7 001	Section 6.2.36 and 6.2.41	Depth to water table beneath the repository.
DIRS 163555	GS010908312332.002. *Borehole Data from Water-Level Data Analysis for the Saturated Zone Site-Scale Flow and Transport Model*. Submittal date: 10/02/2001.	Table S02298_001 Depth to water in the alluvium	Sections 6.2.4 and 6.2.46	Approximate UZ thickness in region near hypothetical pumping well for well ID NC-EWDP 19P (in the alluvium)
		Table S02298_001	Section 6.2.34	G-4 and G-1 water levels and coordinate locations
Justification–Water level measurements and coordinate locations taken from wells specifically drilled to assess depth to water, pump-test, geology, and groundwater conditions within the Yucca Mountain vicinity.				
DIRS 172835	DTN: MO0501MWDBDCFS.000 Biosphere Dose Conversion Factors for the Groundwater Exposure Scenario Calculated Using ICRP 72 Dose Coefficients. Submittal date: 01/26/2005.	GW_BDCFs_ICRP72_Data.xls	Tables 6.2-1	BDCFs for selected radionuclides.
Justification–Biosphere dose conversion factors developed by experts in the field and used in the TSPA-LA for the Yucca Mountain Project.				
DIRS 173521	MO0504MWDNUMWP.001. Number of Waste Packages Hit by Igneous Intrusion. Submittal date: 04/22/2005.	ConduitCDF subsection of spreadsheet: results05b.xls	Section 6.2.4	Distributions of numbers of waste packages hit by igneous dikes under different combinations of dike numbers, spacings, azimuths, widths, and other factors.
Justification–Analysis of number of waste packages brought to surface given repository configuration and predictions of dike widths.				

Table 4.1-1. Input for Excluded SZ FEPs (Continued)

DIRS	Input	Source	Direct Use In	Description
DIRS 171483	DTN:MO0408MWDDDMIO.002. Drift Degradation Model Inputs and Outputs. Submittal date: 08/31/2004.	NUFT Inputs FLAC 3D Inputs & Outputs\TM model\Part_#1_Grid_Thermal FLAC 3D Inputs & Outputs\TM model\Part_#2_Mechanical	Appendix C	Data used for the three-D thermal mechanical analysis to determine the peak temperature and mechanical stresses at the water table.
Justification: Inputs to the 3-D thermal mechanical analysis in Appendix C of this report.				
DIRS 174101	BSC 2005. *Mountain-Scale Coupled Processes (TH/THC/THM) Models.* MDL-NBS-HS-000007 REV 03 Las Vegas, Nevada: Bechtel SAIC Company.	Section 6.5.12 Figures 6.5.12-1, 6.5.12-2	Section 6.2.36	At 10,000 years, thermal-mechanical stresses do not impart significant changes on vertical fracture permeabilities beyond 100 m below the repository.
		Section 6.5.11 Figure 6.5.11-1	Sections 6.2.37	Results indicate the highest thermally induced stresses occur at approximately 100 years within the repository horizon, are horizontal in direction, and are compressive in nature below the repository. Moving away from the repository, stresses dampen.
Justification–Documents an analysis of impact of thermal pulse due to waste emplacement in repository within the Yucca Mountain vicinity by experts in the field.				
DIRS 169989	BSC 2004. *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada.* ANL-MGR-GS-000001 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20041015.0002.	Section 6.2	Sections 6.2.3, 6.2.5	Igneous activity within the Yucca Mountain region is now in a relative quiescent phase.
		Table 7-1 and Section 7.1	Section 6.2.4 and Table 6.2-1	Probability of a dike intersecting the repository footprint: 1.7 x 10^{-8}/year; probability of volcanic eruption within the repository footprint, conditional on dike intersection: 1.3 x 10^{-8}/year; probability of an eruptive event within 10,000 years.

Table 4.1-1. Input for Excluded SZ FEPs (Continued)

DIRS	Input	Source	Direct Use In	Description
Justification–Documents an analysis and frequency of igneous activity within the Yucca Mountain vicinity by experts in the field.				
DIRS 170002	BSC 2004. *Future Climate Analysis.* ANL-NBS-GS-000008 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20040908.0005.	Section 7.1	Section 6.2.9	Prediction of a cooler and wetter glacial transition climatic condition will follow the brief monsoonal period and will persist for about 8,000 to 8,700 years,
Justification–Documents evidence of past global and regional climatic patterns and cycles, and predicts future climatic conditions within the Yucca Mountain region by experts in the field.				
DIRS 170006	BSC 2004. *Saturated Zone Colloid Transport.* ANL-NBS-HS-000031 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20041008.0007.	Sections 6.4.2 and 7.1	Section 6.2.13	Colloid filtering and settling observed in lab and field tests.
Justification–Documents an analysis of colloid characteristics and behavior in Yucca Mountain waters and porous media by experts in the field.				
DIRS 174109	BSC (Bechtel SAIC Company) 2005. *Hydrogeologic Framework Model for the Saturated-Zone Site-Scale Flow and Transport Model*. MDL-NBS-HS-000024 REV 01. Las Vegas, Nevada. Bechtel SAIC Company.	Figures 6-1 and 6-7	Section 6.2.6	Along the predicted SZ transport path, the depth of carbonate aquifer is well below the current water table.
Justification–Documents analysis of geologic properties and stratigraphy taken from boreholes and wells located in the Yucca mountain vicinity.				
DIRS 170009	BSC 2004. *Water-Level Data Analysis for the Saturated Zone Site-Scale Flow and Transport Model.* ANL-NBS-HS-000034 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20041012.0002.	Table 6-4 and Section 6.3.2	Section 6.2.13	The difference between the alluvium head measurement at NC-EWDP 19D and NC-EWDP 19P is 5.3 m, the elevation difference between the bottom of the monitored interval in these two wells is 293 m.
Justification–Documentation of water-level measurements and hydraulic gradients in the SZ.				
DIRS 174191	BSC 2005. *Features, Events, and Processes in UZ Flow and Transport.* ANL-NBS-MD-000001 REV 03. Las Vegas, Nevada: Bechtel SAIC Company.	Section 6.9.11	Section 6.2.37	Effects of thermal loading on faults are excluded in the near field.
		Sections 6.9.12, 6.9.13 and 6.9.14	Sections 6.2.36, 6.2.38, and 6.2.39	Repository induced thermo-mechanical stresses on fractures, rock properties, and repository induced thermal-chemical effects on alteration are excluded in the UZ (near-field).
		Section 6.4.4	Section 6.2.13	Radionuclide bearing particles larger than colloids are not introduced from the UZ to the SZ.
		Section 6.7.2	Section 6.2.41	A screening decision related to gas production from repository components as it affects UZ flow and transport.
Justification–Documents an analysis of UZ flow and transport FEPS in the Yucca Mountain vicinity.				

Table 4.1-1. Input for Excluded SZ FEPs (Continued)

DIRS	Input	Source	Direct Use In	Description
DIRS 170015	BSC 2004. *Recharge and Lateral Groundwater Flow Boundary Conditions for the Saturated Zone Site-Scale Flow and Transport Model.* ANL-NBS-MD-000010 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20041008.0004.	Table 6-3	Section 6.2.4	Estimated recharge flux rates in upper Jackass Flats is 2.21 mm/year.
		Table 6-4	Section 6.2.39	Recharge from the UZ is approximately 7% of the total recharge. Therefore, thermally-induced changes in SZ water chemistry would be significantly diluted.
Justification –Documentation of an analysis that interpolates flow from a large scale regional flow system within the Yucca Mountain area, to that through boundaries of a smaller region embedded within the larger region.				
DIRS 173981	BSC 2005. *Features, Events, and Processes: Disruptive Events.* ANL-WIS-MD-000005 REV 03. Las Vegas, Nevada: Bechtel SAIC Company. ACC:	Section 6.2.1.10	Sections 6.2.7, 6.2.16, 6.2.17, 6.2.18,	Strain produced from a seismic event will be dissipated along existing faults.
		Section 6.2.1.10	Sections 6.2.17	Changes to fault properties (which implicitly affect the fault's hydrologic properties) will tend to occur in a relatively narrow zone, and be on the order of a few meters to, at most, tens of meters wide along the length of the fault.
Justification–Documents an analysis of disruptive events and how they may affect the geology and geologic properties within the vicinity of Yucca Mountain.				
DIRS 168761	SN0310T0505503.004. Initial Radionuclide Inventories for TSPA-LA. Submittal date: 10/27/2003.	spreadsheet: invdtnj.xls	Table 6.2-1	Grams and activity of radionuclides per commercial spent nuclear fuel waste package - nominal case.
Justification: Documents the activity per waste package that are expected to be disposed at Yucca Mountain				
DIRS 174290	BSC (Bechtel SAIC Company) 2005. *Waste Form and In-Drift Colloids-Associated Radionuclide Concentrations: Abstraction and Summary.* MDL-EBS-PA-000004 REV 02. Las Vegas, Nevada: Bechtel SAIC Company	Section 1.2 and Appendix I, Section I-1	Section 6.2.13	(1) Upper limit of colloid diameter. (2) Colloid-particle density (D_p) values.
		Section 6.3.1	Section 6.2.33	Radionuclide bearing colloid formation, transport, and complexation are dominated by natural inorganic ligands and inorganic constituents generated by the degradation of emplaced waste forms
Justification–Documents an analysis of colloids and their characteristics produced from Yucca Mountain waste.				

Table 4.1-1. Input for Excluded SZ FEPs (Continued)

DIRS	Input	Source	Direct Use In	Description
DIRS 170036	BSC 2004. *Site-Scale Saturated Zone Transport.* MDL-NBS-HS-000010 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20041103.0004.	Table 6.6-1b	Section 6.2.39	In the model, no credit is being taken for sorption onto zeolites that reside along the SZ flow path.
		Section 6.3 Appendix F	Section 6.2.26	Model assumes that the SZ groundwaters along the transport path are oxidizing from the UZ-SZ interface to the 18-km compliance boundary.
Justification–Documents an analysis of SZ transport processes for radionuclides through the hydrogeology system in the Yucca Mountain area given likely scenarios and climatic futures. Model assumptions from Section 6 are considered to be reasonable to use as a direct input because these assumptions are inherent to the model which has been validated.				
DIRS 174012	BSC (Bechtel SAIC Company) 2005. Saturated Zone Flow and Transport Model Abstraction. MDL-NBS-HS-000021 REV 03. Las Vegas, Nevada: Bechtel SAIC Company.	Table 6-8	Sections 6.2.3, 6.2.4 Table 6.2-1	Values for K_d, bulk density, sorption, porosity, and retardation factor.
		Section 6.5.2.4, Table 6-8, Figure 6-6	Sections 6.2.3, 6.2.7, 6.2.16, 6.2.17, 6.2.18	Evaluation of uncertainties in flowing interval properties
		Figure 6-28	Sections 6.2.4	800-year SZ transport time starting below the repository footprint to compliance boundary. This is modified by the climate scaling factor to be a 205 year transport time
		Section 6.5.2.2	Sections 6.2.9, 6.2.14, 6.2.15, and 6.2.42	(1) Uncertainty in the volcanic-alluvium contact zone is modeled in the SZ. (2) Undetected features in the SZ are implicitly incorporated in the Transport Abstraction Model through parameter distribution
		Table 6-8	Section 6.2.13	The alluvium mean effective porosity is 0.18.
		Section 6.5.20	Section 6.2.13	Effective porosity in SZ carbonate units is 0.01.
		Section 6.5.2.14	Section 6.2.46	Average total porosity of alluvium is 0.30.
		Table 7-1	Section 6.2.46	Median values of sorption coefficients.
Justification–Documents SZ transport abstraction model for radionuclides through the hydrogeologic system in the Yucca Mountain area given likely scenarios and climatic futures.				

Table 4.1-1. Input for Excluded SZ FEPs (Continued)

DIRS	Input	Source	Direct Use In	Description
DIRS 170768	DTN: LA0407DK831811.001. Physical Parameters of Basaltic Magma and Eruption Phenomena. Submittal date: 07/15/2004.	igneous parameters v3	Section 6.2.3	Dimension of basaltic dikes in the Yucca Mountain vicinity.
Justification–Dimension of mean value for dike widths that may intrude in SZ site-scale model for Yucca Mountain vicinity, which is appropriate for this screening argument.				
153679	DTN: MO0012MAJIONIS.000. Water-Major Ion and Isotope Data. Submittal date: 12/01/2000	Table S00453_001	Sections 6.2.9, 6.2.26 and 6.2.33	Uncorrected SZ groundwater ages determined from carbon-14
Justification: Groundwater ages at Yucca Mountain based upon carbon-14 data.				
DIRS 170037	BSC (Bechtel SAIC Company) 2004. *Saturated Zone Site-Scale Flow Model.* MDL-NBS-HS-000011, Rev. 02. Las Vegas, Nevada: Bechtel SAIC Company.	Figure A6-3 Table 6-17	Section 6.2.5	Evidence of past hydrothermal mineral alteration seen in Calico Hills, Claim Canyon, and along the south flank of Shoshone Mountain, which lie north and northeast of Yucca Mountain, is not along the SZ flow path.
		Section 6.6.2.3	Section 6.2.6,	The transport pathways in the SZ are primarily through volcanic tuffs and alluvial material.
		Figure 6-37, Table 6-17	Sections 6.2.20 and 6.2.32 Figure 6.2-3	(1) Geologic features modeled in the SZ flow region. (2) The Solitario Canyon Splay fault serves as a groundwater divide.
		Table 6-19	Section 6.2.13	Permeability of the (mixed tuff) confining unit between the carbonate aquifer and the Bullfrog unit is 10^{-15} m^2.
		Table 7-4	Section 6.2.13	Mean permeability value for the alluvium is 2.7×10^{-13} m^2.
		Section 6.6.2.3	Sections 6.2.9, 6.2.13	SZ base case flow calculations show transport path under current and wetter climate conditions is mainly in the following units: Prow Pass, Bullfrog, and Tram subunits of Crater Flat Formation, Upper Volcanic Confining Unit, Upper Volcanic Aquifer, Undifferentiated Valley Fill and Alluvium.
		Section 6.6.1.4 Table 6-19	Section 6.2.13	On a regional scale, permeability (which is implicitly fracture permeability) in the Bullfrog, Tram, and Prow Pass units ranges over three orders of magnitude.

Table 4.1-1. Input for Excluded SZ FEPs (Continued)

DIRS	Input	Source	Direct Use In	Description
DIRS 170037 (Continued)	BSC (Bechtel SAIC Company) 2004. *Saturated Zone Site-Scale Flow Model.* MDL-NBS-HS-000011, Rev. 02. Las Vegas, Nevada: Bechtel SAIC Company.	Table 6-18	Section 6.2.13	Carbonate Aquifer hydraulic head measurement is 752.4 m at UE-25p#1 and 730.2 m in shallower units at approximately the same location (wells UE-25c#1, UE-25c#2, UE-25c#3).
		Table 6-17, Figure 6-37 and Figure 6-7	Section 6.2.16	(1) The Bow Ridge Fault is one of many faults incorporated in the Imbricate Fault Zone. (2) Hydrological properties and dimensions of the Imbricate Fault Zone.
		Sections 6.4.3.1, 6.4.3.2 Figure 6-37	Section 6.2.16	The Imbricate Zone has relatively lower anistropy ratios than other volcanic regions in the SZ flow domain.
		Section 6.3.2.3	Section 6.2.17	Solitario Canyon Fault is a groundwater divide between the Yucca Mountain and the Crater Flat regions.
		Section 6.3.3	Section 6.2.19,	SZ flow implicitly models flow through fractures in the volcanic units.
		Table 6-17 and Figure 6-37	Section 6.2.5	Evidence of hydrothermal mineral alteration is seen in the Calico Hills, Claim Canyon, and along the south flank of Shoshone Mountain, but not along the SZ flow path
		Figure 6-37, Table 6-17	Section 6.2.5	Past hydrothermal areas (Calico Hills, Claim Canyon, and along the south flank of Shoshone Mountain) are not along the SZ flow path and lie north and northeast of Yucca Mountain; future igneous activity within the Crater Flat basin will typically cause minimal, highly localized basaltic dike-like intrusions.
		Figure 6-43	Section 6.2.9	Collective thickness of SZ units where most of flow and transport takes place (300 m).
		Appendix A, Table A4-1	Section 6.2.45	Examples of naturally occurring isotopes within the SZ flow domain (^{84}Sr, ^{86}Sr, ^{87}Sr, ^{88}Sr, ^{234}U, ^{238}U, ^{12}C, ^{13}C).
		Table 6-19	Section 6.2.9	The Prow Pass and Bullfrog units are the most permeable volcanic units in the flow and transport path.

Table 4.1-1. Input for Excluded SZ FEPs (Continued)

DIRS	Input	Source	Direct Use In	Description
DIRS 170037 (Continued)	BSC (Bechtel SAIC Company) 2004. *Saturated Zone Site-Scale Flow Model.* MDL-NBS-HS-000011, Rev. 02. Las Vegas, Nevada: Bechtel SAIC Company.	Figure 6-12	Section 6.2.32	The shallow water table corresponds to the three paleospring deposits located along Highway 95 and at the southern end of Crater Flat.
Justification–Documents numerical analysis of potential flow paths between Yucca Mountain and the 18-km boundary. Inputs for the geologic properties and predicted water levels are assessed by subject matter experts. Use of permeability's from the calibrated flow model are considered output of the validated flow model. Use of				
DIRS 149850	Mongano, G.S.; Singleton, W.L.; Moyer, T.C.; Beason, S.C.; Eatman, G.L.W.; Albin, A.L.; and Lung, R.C. 1999. *Geology of the ECRB Cross Drift - Exploratory Studies Facility, Yucca Mountain Project, Yucca Mountain, Nevada.* Deliverable SPG42GM3. Denver, Colorado: U.S. Geological Survey. ACC: MOL.20000324.0614.	pp. 48-65	Sections 6.2.16, 6.2.17, 6.2.18,	Solitario Canyon Fault's cumulative displacement is approximately 260 m where it intersects the ECRB Cross-Drift; with this relatively large displacement, its zone of alteration consists of approximately a 20 m brecciated and gouge zone, and seismically induced fractured area that extends tens of meters from the fault.
Justification–Documents an analysis of disruptive events and how they may effect the geology and geologic properties within the vicinity of Yucca Mountain.				
DIRS 100722	Dean, J.A. 1992. *Lange's Handbook of Chemistry.* 14th Edition. New York, New York: McGraw-Hill. TIC: 240690.	Table 5.14	Section 6.2.34	Density of water at different temperatures.
Justification: Handbook of Chemistry which provides water density as a function of temperature.				

BDCF = biosphere dose conversion factor; DIRS = Document Input Reference System; FEP = feature, event, and process; LA = license application; RN = radionuclide; SZ = saturated zone; TSPA = total system performance assessment; UZ = unsaturated zone;

Table 4.1-2. Direct Input from Regulation 10 CFR Part 63 Used for the SZ FEP Screening

Regulatory Section 10 CFR 63 [DIRS 173273]	Section in the Report	Input Description
63.2	6.2.43	Definition of the reference biosphere in which the RMEI will reside.
63.2, 63.305(a), (b), (c), (d)	5.3, 6.2.11, 6.2.26, 6.2.32, 6.2.46	(1) Justification for assumption that potential and naturally occurring geologic and climatic events (but perhaps not necessarily the magnitude) have occurred at least once in the past within the geologic record and can be used to predict 10,000 years into the future in TSPA. (2) Present socio-economic practices are reflective of future practices (prohibiting changes in society or reference biosphere). (3) Guidance for identifying and examining the effects of FEPs in a performance assessment on the Yucca Mountain disposal system.
63.102 (j)	6.2.46	The disposal system includes the SZ which is part of the natural barrier system.
63.102 (j), 63.114(d), (e), (f), 63.342	4.2.3, 6.1.2 6.2.46	(1) Concept of performance assessment and inclusion or exclusion of FEP. (2) FEP exclusion due to low consequence criteria. (3) FEP exclusion due to low probability criterion.
63.312(a), (b), (c), (d), (e)	6.2.12, 6.2.4, 6.2.21, 6.2.23, 6.2.32, 6.2.46	(1) Characteristics of the RMEI to be used in exposure calculations. (2) Distance from the repository to the receptor location. (3) Volume of water within the reference biosphere used to determine radionuclide concentration (3,000 acre-ft).
63.321	6.2.46	The regulation specifies only a single stylized instance of human interference will occur in the engineered and natural barrier system and no others.
63.332(a)(3)	6.2.4, 6.2.12,6.2.21, 6.2.23,	Representative volume of groundwater used to determine radionuclide concentration (3,000 acre-ft).

FEP = feature, event, and process; RMEI = reasonably maximally exposed individual; SZ=saturated zone; TSPA = total system performance assessment

4.2 CRITERIA

This section addresses the criteria relevant to the FEP screening process. The criteria relevant to the FEP screening process stem from the applicable regulations at 10 CFR Part 63 [DIRS 173273], as identified in the *Project Requirements Document* (PRD) (Canori and Leitner 2003 [DIRS 166275]). These criteria find expression as specific acceptance criteria presented by the U.S. Nuclear Regulatory Commission (NRC) in *Yucca Mountain Review Plan, Final Report* (YMRP) (NRC 2003 [DIRS 163274], Sections 2.2.1.2.1.3 and 2.2.1.2.2.3). The correlation between the regulations and YMRP acceptance criteria is shown in Table 4.2-1. Satisfaction of the criteria is discussed in Section 7.1.

4.2.1 Project Requirements Document

The PRD (Canori and Leitner 2003 [DIRS 166275]) documents and categorizes the regulatory and other Project requirements and provides a crosswalk to the YMP organizations responsible for ensuring that the criteria are addressed in the LA. The regulatory requirements include criteria relevant to performance assessment activities, in general, and to FEP-related activities as they pertain to performance assessment, in particular. Table 4.2-1 provides a crosswalk between the regulatory requirements and the PRD locator for these requirements.

4.2.2 Yucca Mountain Review Plan

The NRC will be reviewing the LA. The basis of the review is described in the YMRP (NRC 2003 [DIRS 163274], Sections 2.2.1.2), and the bases for acceptance are stated as acceptance criteria. In Table 4.2-1, YMRP acceptance criteria are correlated to the corresponding regulations as they pertain to FEP-related criteria.

The cited YMRP (NRC 2003 [DIRS 163274]) criteria are provided in Table 4.2-2. The YMRP acceptance criteria for FEP screening echo the regulatory screening criteria of low probability and low consequence but also allow for exclusion of a FEP if the process is specifically excluded by the regulations (see Section 4.2.3).

Table 4.2-1. Relationships of Regulations to the YMRP Acceptance Criteria

Description of the Applicable Regulatory Requirement or Acceptance Criterion	Regulatory Citation 10 CFR Part 63 [DIRS 173273]	Associated PRD Canori and Leitner 2003 [DIRS 166275]	Associated Criteria in the YMRP [DIRS 163274]
General Requirements and Scope Pertinent to FEP Screening			
Include data related to geology, hydrology, geochemistry, and geophysics. Include information of the design of the engineered barrier system used to define parameters and conceptual models.	63.114(a)	PRD-002/ T-015	2.2.1.2.1.3 Acceptance Criterion 1
Account for uncertainties and variabilities in parameter values and provide the technical basis for parameter ranges, probability distributions, or bounding values.	63.114(b)	PRD-002/ T-015	2.2.1.2.2.3 Acceptance Criteria 2 and 5
FEP Screening Criteria			
Provide the justification and technical basis for excluding FEPs specifically excluded by regulation.	63.114(e)	PRD-002/ T-015	2.2.1.2.1.3 Acceptance Criterion 2
Provide the technical basis for either inclusion or exclusion of FEPs. Provide the justification and technical basis for those excluded based on probability.	63.114(d)	PRD-002/ T-015	2.2.1.2.1.3 Acceptance Criterion 2
Provide the technical basis for either inclusion or exclusion of FEPs. Provide the justification and the technical basis for those excluded based on lack of significant change in resulting radiological exposure or release to the accessible environment.	63.114(e), (f) 43	PRD-002/ T-015	2.2.1.2.1.3 Acceptance Criterion 2

FEP = feature, event, and process; PRD = *Project Requirements Document*

Table 4.2-2. Relevant YMRP Acceptance Criteria

YMRP Section	Acceptance Criterion	Description
Scenario Analysis and Event Probability: Scenario Analysis (from Section 2.2.1.2.1.3 NUREG-1804 [DIRS 163274])	1. The Identification of a list of FEPs Is Adequate	(1) The Safety Analysis Report contains a complete list of FEPs related to the geologic setting or the degradation, deterioration, or alteration of engineered barriers (including those processes that would affect the performance of natural barriers) that have the potential to influence repository performance. The list is consistent with the site characterization data. Moreover, the comprehensive features, events, and processes list includes, but is not limited to, potentially disruptive events related to igneous activity (extrusive and intrusive); seismic shaking (high-frequency-low magnitude, and rare large-magnitude events); tectonic evolution (slip on existing faults and formation of new faults); climatic change (change to pluvial conditions); and criticality.
	2. Screening of the Initial List of Features, Events, and Processes Is Appropriate	(1) The DOE has identified all FEPs related to either the geologic setting, to the degradation, deterioration, or alteration of engineered barriers (including those processes that would affect the performance of natural barriers) that have been excluded. (2) The DOE has provided justification for those FEPs that have been excluded. An acceptable justification for excluding FEPs is that either the FEP is specifically excluded by regulation; probability of the FEP (generally an event) falls below the regulatory criterion; or omission of the FEP does not significantly change the magnitude and time of the resulting radiological exposures to the reasonably maximally exposed individual, or radionuclide releases to the accessible environment. (3) The DOE has provided an adequate technical basis for each FEP excluded from the performance assessment to support the conclusion that either the FEP is specifically excluded by regulation, the probability of the FEP falls below the regulatory criterion, or omission of the FEP does not significantly change the magnitude and time of the resulting radiological exposures to the reasonably maximally exposed individual, or radionuclide releases to the accessible environment.
Scenario Analysis and Event Probability: Identification of Events with Probability Greater than 10^{-8} per Year (from Section 2.2.1.2.2.3 NUREG-1804 [DIRS 163274])	1. Events are Adequately Defined	(1) Events or event classes are defined without ambiguity and used consistently in probability models, such that probabilities for each event or event class are estimated separately.

Table 4.2-2. Relevant YMRP Acceptance Criteria (Continued)

YMRP Section	Acceptance Criterion	Description
Scenario Analysis and Event Probability: (Continued)	(Continued)	(2) Probabilities of intrusive and extrusive igneous events are calculated separately. Definitions of faulting and earthquakes are derived from the historical record, paleoseismic studies, or geological analyses. Criticality events are calculated separately by location.
	2. Probability Estimates for Future Events Are Supported by Appropriate Technical Bases.	(1) Probabilities for future natural events have considered past patterns of the natural events in the Yucca Mountain region, considering the likely future conditions and interactions of the natural and engineered repository system. These probability estimates have specifically included igneous events, faulting and seismic events, and criticality events.
	5. Uncertainty in Event Probability is Adequately Evaluated	(1) Probability values appropriately reflect uncertainties. Specifically: a. The DOE provides a technical basis for probability values used, and the values account for the uncertainty in the probability estimates. b. The uncertainty for reported probability values adequately reflects the influence of parameter uncertainty on the range of model results (i.e., precision) and the model uncertainty, as it affects the timing and magnitude of past events (i.e., accuracy).

DOE = U.S. Department of Energy; FEP = feature, event, and process.

4.2.3 FEPs Screening Criteria

The criteria for determining low probability, low consequence, or by regulation exclusions are described below.

4.2.3.1 Low Probability

The low-probability criterion is stated in 10 CFR 63.114(d) [DIRS 173273]:

> Consider only events that have at least one chance in 10,000 of occurring over 10,000 years.

and supported by 10 CFR 63.342:

> The Department of Energy's (DOE) performance assessments shall not include consideration of very unlikely features, events, or processes, i.e., those that are estimated to have less than one chance in 10,000 of occurring within 10,000 years of disposal.

As noted in Assumption 5.2, the low-probability criterion for very unlikely events corresponds to an annual-exceedance probability of 10^{-8}.

4.2.3.2 Low Consequence

The low consequence criterion is stated in 10 CFR 63.114(e), (f) [DIRS 173273]:

> (e) Provide the technical basis for either inclusion or exclusion of specific features, events, and processes in the performance assessment. Specific features, events, and processes must be evaluated in detail if the magnitude and time of the resulting radiation exposure to the reasonably maximally exposed individual, or radionuclide releases to the accessible environment, would be significantly changed by their omission.
>
> (f) Provide the technical basis for either inclusion or exclusion of degradation, deterioration, or alteration processes of engineered barriers in the performance assessment, including those processes that would adversely affect the performance of natural barriers. Degradation, deterioration, or alteration processes of engineered barriers must be evaluated in detail if the magnitude and time of the resulting radiological exposures to the reasonably maximally exposed individual, or radionuclide releases to the accessible environment, would be significantly changed by their omission.

and supported by 10 CFR 63.342]DIRS 173273]:

> DOE's performance assessments need not evaluate the impacts resulting from any features, events, and processes or sequences of events and processes with a higher chance of occurrence if the results of the performance assessments would not be changed significantly.

Some FEPs have a beneficial effect on the TSPA, as opposed to an adverse effect. As identified in 10 CFR 63.102(j) [DIRS 173273], the concept of a performance assessment includes:

> The features, events, and processes considered in the performance assessment should represent a wide range of both beneficial and potentially adverse effects on performance (e.g., beneficial effects of radionuclide sorption; potentially adverse effects of fracture flow or a criticality event). Those features, events, and processes expected to materially affect compliance with 10 CFR 63.113(b) [DIRS 173273] or be potentially adverse to performance are included, while events (event classes or scenario classes) that are very unlikely (less than one chance in 10,000 over 10,000 years) can be excluded from the analysis.

The YMRP (NRC 2003 [DIRS 163274], Section 2.2.1), states that:

> In many regulatory applications, a conservative approach can be used to decrease the need to collect additional information or to justify a simplified modeling approach. Conservative estimates for the dose to the reasonably maximally exposed individual may be used to demonstrate that the repository meets U.S. Nuclear Regulatory Commission regulations and provides adequate protection of public health and safety. The total system performance assessment is a complex analysis with many parameters, and the U.S. Department of Energy may use conservative assumptions to simplify its approaches and data collection needs. However, a technical basis that supports the selection of models and parameter ranges or distributions must be provided.

On the basis of these statements, those FEPs that are demonstrated to have only beneficial effects on the radiation exposure to the RMEI, or radionuclide releases to the accessible environment, can be excluded on the basis of low consequence because they have no adverse effects on performance.

4.2.3.3 By Regulation

The YMRP (NRC 2003 [DIRS 163274], Section 2.2.1.2.1.3, Acceptance Criterion 2 allows for exclusion of a FEP if the process is specifically excluded by the regulations:

> The DOE has provided justification for those FEPs that have been excluded. An acceptable justification for excluding FEPs is that either the FEP is specifically excluded by regulation; probability of the FEP (generally an event) falls below the regulatory criterion; or omission of the feature, and process does not significantly change the magnitude and time of the resulting radiological exposures to the reasonably maximally exposed individual, or radionuclide releases to the accessible environment.

4.3 CODES, STANDARDS, AND REGULATIONS

No codes, standards, or regulations other than those identified in *Project Requirements Document* (Canori and Leitner 2003 [DIRS 166275], Table 2-3) and determined to be applicable (Table 4.2-1) were used in this analysis.

5. ASSUMPTIONS

Each assumption made in this analysis contains a description of where it is applied and justification for its use.

5.1 ASH FALL LEACHING AND SZ TRANSPORT

The following assumption is made to estimate the potential impact of leaching contaminants from ash fall on the release to the accessible environment (FEP 1.2.04.07.0B, Ash Redistribution in Groundwater, Section 6.2.4 of this document).

Assumption–A volcanic eruption occurs immediately after waste emplacement.

Justification–An assumption that a volcanic eruption occurs immediately after waste emplacement maximizes the impact of short-lived radionuclides, contributing to radiation exposure to the RMEI, with regard to the timing of the release. No further verification is needed.

5.2 PROBABILITY CRITERION

The following assumption is applicable to FEPs related to seismic and igneous activity. They include FEPs 1.2.04.02.0A–Igneous activity changes rock properties (Section 6.2.3); 1.2.04.07.0B–Ash redistribution in groundwater (Section 6.2.4); 1.2.10.01.0A–Hydrologic response to seismic activity (Section 6.2.7); 1.2.10.02.0A–Hydrologic response to igneous activity (Section 6.2.8); 2.2.06.01.0A–Seismic activity changes porosity and permeability of rock (Section 6.2.16); 2.2.06.02.0A–Seismic activity changes porosity and permeability of faults (Section 6.2.17); and 2.2.06.02.0B–Seismic activity changes porosity and permeability of fractures (Section 6.2.18).

Assumption–For postclosure naturally occurring FEPs, the probability criterion also can be expressed as an annual exceedance probability (i.e., the probability that a specified value, will be exceeded during one year). The annual exceedance probability should be applied to ground motions or fault displacement while an annual frequency of occurrence should be applied to igneous hazards. More specifically, a stated probability-screening criterion of 1 chance in 10,000 in 10,000 years ($10^{-4}/10^4$ year) is equivalent to a 10^{-8} annual-exceedance probability or annual-exceedance frequency. A stated definition of unlikely events as having one chance in ten in 10,000 years ($10^{-1}/10^4$ year) of occurring is equivalent to a 10^{-5} annual-exceedance probability or annual-exceedance frequency.

Justification–The definition of annual-exceedance probability and the following justification for this assumption are taken from *Characterize Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada* (BSC 2004 [DIRS 168030], Glossary).

The assumption of equivalence of annual-exceedance probability is appropriate if the possibility of an event is equal for any given year. This satisfies the definition of a Poisson distribution as “a probability density function that is often used as a mathematical model of the number of outcomes obtained in a suitable interval of time and space, that has its mean equal to its variance…."[1] This is inferred to mean that naturally occurring, infrequent, and independent events can be represented as stochastic processes in which distinct events occur in such a way that the number of events occurring in a given period of time depends only on the length of the time period. The use of this assumption is justified in *Characterize Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada* (BSC 2004 [DIRS 168030], Section 6.4.2), which indicates that assuming that the behavior of the earth is generally Poissonian or random is the underlying assumption in all probabilistic hazard analyses.

In other words, naturally occurring events (e.g., earthquakes, meteorite impacts) are considered as independent events with regard to size, time, and location. Although there may be cases where sufficient data and information exist to depart from this assumption, the Poissonian model is generally an effective representation of nature and represents a compromise between the complexity of natural processes, availability of information, and the sensitivity of results of engineering relevance. Consequently, for natural processes that occur over long time spans, assuming annual equivalence over a 10,000-year period (a relatively short time span) is reasonable and consistent with the basis of probabilistic hazard analyses. Therefore, no further confirmation is required.

5.3 EVOLUTION OF THE GEOLOGIC SETTING AND CLIMATE

Assumption–Potential naturally occurring events, perhaps of different magnitude, have occurred at least once in the past within the geologic record used as the basis for determining factors that could affect the Yucca Mountain disposal system over the next 10,000 years.

Justification–This assumption is justified because it is consistent with the regulations used as direct input. At 10 CFR 63.305(c) [DIRS 173273], DOE is directed to "vary factors related to the geology, hydrology, and climate based upon cautious, but reasonable assumptions consistent with present knowledge of factors that could affect the Yucca Mountain disposal system over the next 10,000 years."

The implication of this assumption is that any discernible impacts or processes related to past events at the site setting are reflected in the present knowledge of natural processes that form the basis of the TSPA. If the subject FEP phenomena are not reflected or discernible in the data used to describe past settings, then they are either of low consequence or of low probability and can be excluded from consideration. Because it is consistent with the regulations, no further confirmation is necessary.

<u>Use</u>: This assumption is germane to FEPs related to processes or phenomena that, speculatively, could affect future states of the system, but for which the magnitude of and/or coupling to the effect on the repository is not well defined, or for which consequences in present time are known to be minor. These types of events are known to occur. However, the effects of the phenomenon or the effects associated with varying magnitudes of the event type and probabilities are not well documented (e.g., effects of a supernova); the form of the coupling process is not well defined

[1] *Merriam-Webster's Collegiate Dictionary*, 10th ed., s.v. "Poisson distribution."

(e.g., changes in the earth's magnetic field); or the phenomenon has been shown to have no impact or insignificant impact at the present time (e.g., earth tides).

This assumption is used throughout and is particularly germane for FEPs 1.3.07.01.0A– Water table decline (Section 6.2.9); 1.3.07.02.0A–Water table rise affects SZ (Section 6.2.10); 2.2.06.01.0A–Seismic activity changes porosity and permeability of rock (Section 6.2.16); 2.2.06.02.0A–Seismic activity changes porosity and permeability of faults (Section 6.2.17); 2.2.06.02.0B–Seismic activity changes porosity and permeability of fractures (Section 6.2.18); 2.2.08.01.0A–Chemical characteristics of groundwater in the SZ (Section 6.2.25); and 2.2.08.03.0A–Geochemical interactions and evolution in the SZ (Section 6.2.26).

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6. SCIENTIC ANALYSIS DISCUSSION

The following sections discuss the SZ FEP analyses. Section 6.1 of this report discusses the methods and approach used for the FEP screening. Sections 6.2.1 to 6.2.46 provide the screening documentation.

6.1 APPROACH

The identification and screening of a comprehensive list of FEPs potentially relevant to the postclosure performance of the Yucca Mountain repository is an ongoing, iterative process based on site-specific information, design, and regulations. FEP analysis uses the following definitions, as taken from the YMRP (NRC 2003 [DIRS 163274], Glossary):

feature – An object, structure, or condition that has a potential to affect disposal system performance.

event – A natural or human-caused phenomenon that has a potential to affect disposal system performance and occurs during an interval that is short compared to the period of performance.

process – A natural or human-caused phenomenon that has a potential to affect disposal system performance and operates during all or a significant part of the period of performance.

FEP analysis for TSPA-LA is described in *the Development of the Total System Performance Assessment-License Application Features, Events, and Processes* (BSC 2005 [DIRS 173800]). It is summarized in the following subsections.

6.1.1 FEP Identification

The first step of FEP analysis is FEP identification and classification, which addresses Acceptance Criterion 1 of the YMRP (NRC 2003 [DIRS 163274], Section 2.2.1.2.1.3). The TSPA-LA FEP identification and classification process is described in *The Development of the Total System Performance Assessment-License Application Features, Events, and Processes* (BSC 2005 ([DIRS 173800], Section 3). This process produced a version of the LA FEP list (DTN: MO0501SEPFEPLA.001 [DIRS 172601]) used as input in this SZ FEP analysis.

6.1.2 FEP Screening Process

The second step of FEP analysis is FEP screening, which addresses Acceptance Criterion 2 of the YMRP (NRC 2003 [DIRS 163274], Section 2.2.1.2.1.3). The TSPA-LA FEP screening process is described in *the Development of the Total System Performance Assessment-License Application Features, Events, and Processes* (BSC 2005 [DIRS 173800], Section 4).

For FEP screening, each FEP is screened against the specified exclusion criteria (see Section 4.2.3), summarized in the following FEP screening statements:

- FEPs having less than one chance in 10,000 of occurring over 10,000 years may be excluded (screened out) from the TSPA on the basis of low probability (as per 10 CFR 63.114(d) and 63.342 [DIRS 173273]).

- FEPs whose omission would not significantly change the magnitude and time of the resulting radiological exposures to the RMEI, or radionuclide releases to the accessible environment, may be excluded (screened out) from the TSPA on the basis of low consequence (as per 10 CFR 63.114(e), (f) and 63.342 [DIRS 173273]).

- FEPs that are inconsistent with the characteristics, concepts, and definitions specified in 10 CFR Part 63 [DIRS 173273] may be excluded (screened out) from the TSPA by regulation.

A FEP need only satisfy one of the exclusion screening criteria to be excluded from TSPA. A FEP that does not satisfy any of the exclusion screening criteria must be included (screened in) in the TSPA-LA model.

This report documents the screening decisions for the SZ FEPs. In cases where a FEP covers multiple technical areas and is shared with other FEP reports, this report provides only a partial technical basis for the screening decision as it relates to SZ issues. The full technical basis for these shared FEPs is addressed, collectively, by all of the sharing FEP analysis reports. Documentation of the screening for each FEP is provided in Section 6.2 using the following standardized format. There may be instances where additional text is presented for either included or excluded FEPs. The text provides background information and/or a high level of detail supporting either the exclusion argument or the TSPA-LA disposition.

Section Number (e.g., Section 6.2.x) FEP Name (FEP Number)

FEP Description: This field describes the nature and scope of the FEP under consideration.

Screening Decision: Identifies the screening decision as one of:

"Included"
"Excluded – Low Probability"
"Excluded – Low Consequence"
"Excluded – By Regulation"

In a few cases, a FEP may be excluded by a combination of two criteria (e.g., Low Probability and Low Consequence).

Screening Argument: This field is used only for excluded FEPs. It provides the discussion for why a FEP has been excluded from TSPA-LA.

TSPA Disposition: This field is used only for included FEPs. It provides the consolidated discussion of how a FEP has been included in TSPA-LA, making reference to more detailed documentation in other supporting technical reports, as applicable.

Supporting Reports: This field is only used for included FEPs. It provides the list of supporting technical reports that identified the FEP as an included FEP and contain information relevant to the implementation of the FEP within the TSPA-LA model. This list of supporting technical reports provides traceability of the FEP through the document hierarchy. For excluded FEPs, it is indicated as "Not Applicable".

Supplemental Discussion: This provides additional or detailed information to support the screening argument or disposition.

6.1.3 Supporting Reports and Inputs

Table 6.1-1 provides a list of SZ model and analysis reports that support the rationale for those SZ FEPs included in the TSPA-LA. Some SZ analysis and model reports provide expanded discussions of a FEP topic, while other reports discuss a FEP topic in only a cursory fashion. The rationale for excluding an SZ FEP is provided in this report. The sources of data and technical information used in the screening arguments are cited within each FEP discussion provided in this report. The TSPA-LA dispositions of included FEPs are provided in this report as well.

Table 6.1-1. SZ Analysis and Model Reports Used to Support SZ Included FEPs

TSPA- LA FEP Number FEP Name	Supporting Analysis and Model Reports Used in Developing the TSPA Disposition
1.2.02.01.0A Fractures	• *Hydrogeologic Framework Model for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2005 [DIRS 174109]) • *Probability Distribution for Flowing Interval Spacing* (BSC 2004 [DIRS 170014]) • *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036]) • *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037]) • *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]) • *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010])
1.2.02.02.0A Faults	• *Hydrogeologic Framework Model for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2005 [DIRS 174109]) • *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036]) • *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037]) • *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]) • *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010])

Table 6.1-1. SZ Analysis and Model Reports Used to Support SZ Included FEPs (Continued)

TSPA- LA FEP Number FEP Name	Supporting Analysis and Model Reports Used in Developing the TSPA Disposition
1.3.07.02.0A Water table rise affects SZ	• *Water-Level Data Analysis for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2004 [DIRS 170009]) • *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036]) • *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037]) • *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012])
1.4.07.01.0A Water management activities	• *Water-Level Data Analysis for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2004 [DIRS 170009]) • *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012])
1.4.07.02.0A Wells	• *Water-Level Data Analysis for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2004 [DIRS 170009]) • *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037]) • *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012])
2.2.03.01.0A Stratigraphy	• *Hydrogeologic Framework Model for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2005 [DIRS 174109]) • *Probability Distribution for Flowing Interval Spacing* (BSC 2004 [DIRS 170014]) • *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036]) • *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037]) • *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]) • *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010])
2.2.03.02.0A Rock properties of host rock and other units	• *Hydrogeologic Framework Model for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2005 [DIRS 174109]) • *Probability Distribution for Flowing Interval Spacing* (BSC 2004 [DIRS 170014]) • *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036]) • *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037]) • *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]) • *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010])
2.2.07.12.0A Saturated Zone groundwater flow in the geosphere	• *Recharge and Lateral Groundwater Flow Boundary Conditions for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2004 [DIRS 170015]) • *Probability Distribution for Flowing Interval Spacing* (BSC 2004 [DIRS 170014]) • *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037]) • *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036]) • *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]) • *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010])

Table 6.1-1. SZ Analysis and Model Reports Used to Support SZ Included FEPs (Continued)

TSPA- LA FEP Number FEP Name	Supporting Analysis and Model Reports Used in Developing the TSPA Disposition
2.2.07.13.0A Water-conducting features in the SZ	• *Hydrogeologic Framework Model for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2005 [DIRS 174109]) • *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037]) • *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036]) • *Probability Distribution for Flowing Interval Spacing* (BSC 2004 [DIRS 170014]) • *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]) • *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010])
2.2.07.15.0A Advection and dispersion in the SZ	• *Recharge and Lateral Groundwater Flow Boundary Conditions for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2004 [DIRS 170015]) • *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036]) • *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037]) • *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]) • *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010])
2.2.07.16.0A Dilution of radionuclides in groundwater	• *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036]) • *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012])
2.2.07.17.0A Diffusion in the SZ	• *Probability Distribution for Flowing Interval Spacing* (BSC 2004 [DIRS 170014]) • *Saturated Zone Colloid Transport* (BSC 2004 [DIRS 170006]) • *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036]) • *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]) • *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010])
2.2.08.01.0A Chemical characteristics of groundwater in the SZ	• *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036]) • *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037]) – Appendix A • *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012])
2.2.08.06.0A Complexation in the SZ	• *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036]) • *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012])
2.2.08.08.0A Matrix diffusion in the SZ	• *Probability Distribution for Flowing Interval Spacing* (BSC 2004 [DIRS 170014]) • *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036]) • *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]) • *Saturated Zone Colloid Transport* (BSC 2004 [DIRS 170006]) • *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010])
2.2.08.10.0A Colloidal transport in the SZ	• *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036]) • *Saturated Zone Colloid Transport* (BSC 2004 [DIRS 170006]) • *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]) • *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010])

Table 6.1-1. SZ Analysis and Model Reports Used to Support SZ Included FEPs (Continued)

TSPA- LA FEP Number FEP Name	Supporting Analysis and Model Reports Used in Developing the TSPA Disposition
2.2.08.09.0A Sorption in the SZ	• *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036]) • *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]) • *Saturated Zone Colloid Transport* (BSC 2004 [DIRS 170006]) • *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010])
2.2.10.03.0A Natural geothermal effects on flow in the SZ	• *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036]) • *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037]) • *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012])
2.2.12.00.0B Undetected features on the SZ	• *Hydrogeologic Framework Model for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2005 [DIRS 174109]) • *Probability Distribution for Flowing Interval Spacing* (BSC 2004 [DIRS 170014]) • *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036]) • *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037]) • *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]) • *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010])
3.1.01.01.0A Radioactive decay and ingrowth	• *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012])

FEP = feature, event, and process; LA = license application; SZ = saturated zone; TSPA = total system performance assessment.

6.1.4 Qualification of Unqualified Direct Inputs

Unqualified data used elsewhere in the report are qualified in Appendix A.

6.1.5 Assumptions and Simplifications

For included FEPs, the TSPA dispositions may include statements regarding assumptions made to implement the FEP within the TSPA-LA model. Such statements are descriptive of the manner in which the FEP has been included and are not used as the basis of the screening decision to include the FEP with the TSPA-LA model. Because the individual FEPs are specific in nature, any discussion of applicable mathematical formulations, equations, algorithms, numerical methods, or idealizations or simplifications is provided within the individual FEP discussions in Section 6.2.

6.1.6 Intended Use and Limitations

The intended use of this report is to provide FEP screening information for a Project-specific FEP database, and to promote traceability and transparency regarding FEP screening. This report is intended to be used as the source documentation for the FEP database described in *The Development of the Total System Performance Assessment-License Application Features, Events, and Processes* (BSC 2005 [DIRS 173800]). For included FEPs, this document summarizes and consolidates the method of implementation of the FEP in TSPA-LA in the form of TSPA disposition statements, based on more detailed implementation information in the listed supporting technical reports. For excluded FEPs, this document provides the technical basis for exclusion in the form of screening arguments.

Inherent in this evaluation approach is the limitation that the repository will be constructed, operated, and closed according to the design used as the basis for the FEP screening and in accordance with NRC license requirements. This is inherent in performance evaluation of any engineering project, and design verification and performance confirmation are required as part of the construction and operation processes. The results of the FEP screening presented herein are specific to the repository design evaluated in this report for TSPA-LA. Any changes in direct inputs listed in Section 4.1, in baseline conditions used for this evaluation, or in other subsurface conditions, will need to be evaluated to determine if the changes are within the limits stated in the FEP evaluations. Engineering and design changes are subject to evaluation to determine if there are any adverse manner impacts to safety as codified at 10 CFR 63.73 and in Subparts F and G [DIRS 173273]. See also the requirements at 10 CFR 63.44 and 10 CFR 63.131 [DIRS 173273].

6.2 ANALYSIS OF SZ FEPS

Screening information for each of the 46 SZ FEPs is presented in separate subsections. FEPs are addressed in numerical order based on the FEP number except for FEP number 1.4.07.03.0A (Section 6.2.46). The FEP description for FEP 3.1.01.01.0A (Section 6.2.44) has been changed slightly from the description in DTN: MO0501SEPFEPLA.001 [DIRS 172601]. The changes are for editorial clarification and do not change the technical scope of the FEP.

6.2.1 Fractures (1.2.02.01.0A)

FEP Description: Groundwater flow in the Yucca Mountain region and transport of any released radionuclides may take place along fractures. The rate of flow and the extent of transport in fractures are influenced by characteristics such as orientation, aperture, asperity, fracture length, connectivity, and the nature of any linings or infills.

Screening Decision: Included

Screening Argument: N/A

TSPA Disposition:

Groundwater flow through fractures in the volcanic units is included in the SZ flow and transport model *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]). Groundwater flow through fractures in the volcanic units is modeled in the *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037], Sections 6.3.3, 6.5.1,) using an effective continuum approach (BSC 2004 [DIRS 170037], Section 6.5.1) implemented in the numerical code FEHM V2.20 STN: 10086-2.20-00 (LANL 2003 [DIRS 161725]). Observations at Yucca Mountain indicate that in the fractured volcanic units delineated in the hydrogeologic framework model (BSC 2005 [DIRS 174109]), the flow is primarily through the fracture network instead of the matrix. Furthermore, at the scales of interest (hundreds of meters to kilometers), the fracture networks appear to be well-connected over large distances. The drawdown response to pumping at wells surrounding the C-Wells complex in multiwell pump tests indicates a well-connected fracture network in the Miocene tuffaceous rocks in this area (Geldon et al. 1997 [DIRS 100397]; Geldon et al. 1998 [DIRS 129721], p. 31; BSC 2004 [DIRS 170010], Section 6.2). In addition, Finsterle (2000 [DIRS 151875]) demonstrated through the comparison of continuum models and discrete fracture models that the continuum approach is valid for predicting long-term average seepage rates. These findings support the use of the continuum approach to simulate groundwater flow in fractured rocks in the SZ, a larger scale process than drift seepage and, thus, more accurately represented as a continuum.

Therefore, a continuum approach was adopted to simulate groundwater flow through the fractured rock in the SZ. Several continuum approaches are available, including single continuum, dual porosity, and dual permeability–dual porosity. The single continuum approach is the porous media approach. The dual-permeability approach is for heterogeneous media that contains distinct and variable permeability zones lying within close proximity to one another. In such a system, permeability differences between these zones are within a few orders of magnitude of one another. Consequently, advective flow occurs in these regions with distinctively different flow rates. Therefore, a dual-permeability model is needed to predict flow and transport through this type of system.

The dual-porosity approach simulates the flow of water in a heterogeneous system where zonal permeabilities differ by several orders-of-magnitude. This method is useful for simulating flow and transport in fractured media where the permeability of the matrix is much less than in the fractures, as is the case for fractured tuff units in the SZ. Flow occurs in the fractures, but allows for interaction by diffusion with the water in the matrix. In this case, the matrix acts as a large storage reservoir for water and solutes. From a flow perspective, steady-state flow in fractured media could be successfully simulated with a single-continuum approach. However, considerations of transport processes, primarily matrix diffusion, require the implementation of a dual-porosity effective continuum approach in fractured tuff in the SZ (BSC 2004 [DIRS 170036], Section 6.3).

As discussed in *Probability Distribution for Flowing Interval Spacing* (BSC 2004 [DIRS 170014], Section 6.3), only a subset of existing fractures is observed to transmit flow in the SZ. The hydrogeologic characteristics of these "flowing fractures" zones vary from borehole to borehole. In the SZ transport abstraction model and the one-dimensional transport model, (both discussed in *Saturated Zone Flow and Transport Model Abstraction* [BSC 2005 [DIRS 174012], Sections 6.3.1 and 6.3.2]), variability in the groundwater specific discharge, due to variability in fracture permeability and orientation, is modeled by scaling the base-case–specific discharge flow field (BSC 2004 [DIRS 170037], Section 8.3.1) with the stochastically sampled scaling parameters for groundwater specific discharge (GWSPD), and horizontal anisotropy in the volcanic units (HAVO). Additionally, the characteristics of the fracture properties, such as fracture orientation, aperture size, degree of infilling, and tortuosity are modeled through the following probabilistically modeled parameters: GWSPD, flowing interval spacing in the volcanic units (FISVO), flowing interval porosity (FPVO) in the volcanic units, longitudinal dispersivity (LDISP), HAVO, colloid retardation factors in the volcanic units (CORVO), and the radionuclide sorption coefficients between the rock surfaces (which implicitly includes fracture linings and brecciated-fractured zones in the volcanic units) for the radionuclides plutonium and cesium (Kd_Pu_Vo and Kd_Cs_Vo) and americium, thorium, and protactinium (collectively modeled with the parameter Kd_Am_ Vo). The above parameters are described in *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012], Sections 6.5.2.1, 6.5.2.4, 6.5.2.5, 6.5.2.9, 6.5.2.10, 6.5.2.11, and 6.5.2.12 and Table 6-8).

Supporting Reports:

- *Hydrogeologic Framework Model for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2005 [DIRS 174109])
- *Probability Distribution for Flowing Interval Spacing* (BSC 2004 [DIRS 170014])
- *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037])
- *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036])
- *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012])
- *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010]).

6.2.2 Faults (1.2.02.02.0A)

FEP Description: Numerous faults of various sizes have been noted in the Yucca Mountain region, and specifically in the repository area. Faults may represent an alteration of the rock permeability and continuity of the rock mass, an alteration or short-circuiting of the flow paths and flow distributions close to the repository, and/or unexpected pathways through the repository.

Screening Decision: Included

Screening Argument: N/A

TSPA Disposition:

Geologic features and hydrostratigraphic units are explicitly included in the *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]), Section 6.3.1) in a configuration that accounts for the effects of existing faults based on the hydrogeologic framework model (BSC 2005 [DIRS 174109], Section 8). As discussed in *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037], Section 6.5.3.1) and *Hydrogeologic Framework Model for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2005 [DIRS 174109], Section 8), the hydrogeologic framework model represents a simplified representation of faults and other hydrogeologic features (such as zones of hydrothermal alteration) that affect SZ flow and provides a basis on which SZ site-scale flow model is developed.

The hydrogeologic properties of these discrete features are developed in *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037], Section 6.3.2.2). Faults in the model area can dip at almost any angle, but most are high-angle faults. Given numerical flow model resolution, faults were treated as vertical features. Hydraulic testing in the volcanic units of the saturated zone has investigated large volumes of the aquifer, assessing the anisotropy in permeability, which may be influenced by faults (BSC 2004 [DIRS 170010], Section 6.2.6). Faults in the SZ site-scale flow model domain with an apparent impact on groundwater flow and necessary to achieve flow model calibration were explicitly included in the model. Numerous faults occur near Yucca Mountain, and some of these faults greatly affect groundwater flow patterns because they may act as preferred conduits or barriers to groundwater flow (BSC 2004 [DIRS 170037], Sections 6.3.2.2 and 6.3.2.10). Additionally, faults can enhance dispersion by affecting heterogeneities in permeability along SZ flow paths (BSC 2004 [DIRS 170036], Section 6.3). Important thrust faults were represented by repeating hydrogeologic units in the hydrogeologic framework model (BSC 2004 [DIRS 170037], Section 6.5.3.1).

The offsets of hydrostratigraphic units across major faults are incorporated into the model, and some key faults (e.g., Solitario Canyon fault, Highway 95 fault, and Fortymile Wash structure) are explicitly included as high- or low-permeability features.

Model parameters, including HAVO and GWSPD, implicitly include the potential impacts of faults on groundwater flow and are modeled probabilistically to account for the uncertainty in hydrologic properties associated with faults and fractures in the volcanic units. The HAVO and GWSPD parameters are described in *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012], Sections 6.5.2.1 and 6.5.2.10). A more detailed description of the manner in which specific faults have been addressed is provided in the following *Supplemental Discussion* for this FEP in the SZ FEP report.

Supporting Reports:

- *Hydrogeologic Framework Model for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2005 [DIRS 174109])
- *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037])
- *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036])
- *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012])
- *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010]).

Supplemental Discussion:

Faults fall under several distinct categories based on their hydrological impact on SZ flow paths and distributions (BSC 2004 [DIRS 170037], Table 6-17). A list of the modeled faults also denoted as features in *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037], Section 6.5.3.4), aggregated under their hydrologic categories, is given below. Note in the *Supplemental Discussion* of FEP 2.2.07.13.02A–Water Conducting Features in the SZ, a list of features, including faults, developed in *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037]) is given accompanied by a figure (Figure 6.2-3) depicting their location.

(1) Zones of permeability enhancement parallel to faults and zones of permeability reduction perpendicular to faults

- **Crater Flat Fault–**This is a linear feature running north-south in the western half of the model, starting south of Claim Canyon and terminating near Highway 95, almost halfway between Solitario Canyon and the western boundary of the SZ site-scale model. Vertically, it extends from the top to the bottom of the model.

- **Solitario Canyon Fault Zone–**This is a north-south trending linear feature just to the west of Yucca Mountain. Vertically, it extends from the bottom to the top of the model.

- **Solitario Canyon Fault, East Branch–**This is a north-northeast trending linear feature just to the east of Yucca Mountain. Vertically, it extends from the bottom to the top of the model.

- **Solitario Canyon Fault, West Branch–**A north-northeast trending linear features just to the west of Yucca Mountain. Vertically, it extends from the bottom model to the top of the model.

- **Highway 95 Fault (West)**–This is a linear feature in the lower half of the western portion of the model. It is east-southeast trending. Vertically, it extends from the bottom to the top of the model.

(2) Fault Zones with enhanced permeability

- **Bare Mountain Fault–**This is a northwest- to southeast-trending linear feature in the southwestern corner of the model. Vertically, it extends from the bottom to the top of the model.

- **Imbricate Fault Zone**–This is a highly faulted area bounded in the west by the Ghost Dance fault, south by the Dune Wash fault, east by the Paintbrush Canyon fault, and to the north by the Drill Hole Wash fault. Vertically, it extends from the top of the model down through the middle volcanic units to the top of the undifferentiated units.

6.2.3 Igneous Activity Changes Rock Properties (1.2.04.02.0A)

FEP Description: Igneous activity near the underground facility may cause extreme changes in rock stress and the thermal regime, and may lead to rock deformation, including activation, creation, and sealing of faults and fractures. This may cause changes in the rock hydrologic and mineralogic properties. Permeabilities of dikes and sills and the heated regions immediately around them can differ from those of country rock. Mineral alterations can also change the chemical response of the host rock to contaminants.

Screening Decision: Excluded–Low consequence

Screening Argument:

Volcanism and igneous activity within the Yucca Mountain region have undergone two developmental phases. Silicic volcanism was dominant between 11 million and 15 million years ago (Ma), coincident with plate extension and an episode of major caldera formation in the Great Basin Region. As extension rates declined, silicic volcanism was replaced with basaltic volcanism. Basaltic volcanism within the Yucca Mountain region commenced during the later part of the caldera-building phase, around 9 Ma. Postcaldera building basaltic igneous activity within the Yucca Mountain peaked approximately 7 Ma. Volcanism and igneous activity within the Yucca Mountain region are now in a relatively quiescent phase; future igneous activity in the Yucca Mountain region will be basaltic in origin (BSC 2004 [DIRS 169989], Section 6.2). The reduction in igneous activity is coupled with a reduction in basaltic intrusions within SZ stratigraphic units. Thus, on a regional scale, particularly within the next 10,000 years, changes in existing SZ rock properties due to future basaltic intrusions will be less than the cumulative effect of igneous intrusions that occurred over the last 11 million to 13 million years. Uncertainty exists regarding the impacts of past basaltic intrusions on the SZ site-scale groundwater flow system, but no such features have been explicitly included as having an impact on the calibration of the SZ site-scale flow model (BSC 2004 [DIRS 170037], Table 6-17).

Basaltic intrusions due to igneous activity would be an unlikely event, and if one occurred, it would be highly localized, causing minimal to localized changes in the hydrogeologic and physical properties (e.g., lower permeability of the intrusion relative to the matrix of the nonwelded units) of the intruded (country) rock. This is supported by investigations at the Grants Ridge analogue site, which indicates that basaltic intrusion produced only localized formation of volcanic glass within the contact zone (CRWMS M&O 1998 [DIRS 105347], Section 5, p. 74). Investigations of basaltic intrusions at Paiute Ridge (Carter Krogh and Valentine 1996 [DIRS 160928], pp. 7 to 8) suggest that igneous activities altered rock properties from only a few tens of centimeters to, at most, a meter perpendicular to an intruding dike. Because the SZ contains completely saturated pores, heat transfer will occur through both conduction and convection. The heat produced from the dike, which is a primary component in mineral alteration, will be transferred more efficiently away from the dike in the SZ compared to the unsaturated zone (UZ). Therefore, it is inferred that mineral alteration in the SZ due to a dike intrusion will be similar to that of the Grants Ridge analogue site, where mineral alteration is constrained to a narrow width on either side of the dike.

The limited meter-scale effects of mineral alteration and possible change in flow paths are insignificant when compared to the multikilometer scale changes in path length that result from existing considerations of uncertainty in fracture properties and flowing intervals. Flow and transport in the SZ is dominated by existing fractures, fracture clusters, and fracture spacing collectively labeled as flowing intervals in the SZ flow and transport model abstraction (BSC 2005 [DIRS 174012], Section 6.5.2.4). The SZ flow and transport model evaluates uncertainties assigned to flowing interval properties, such as HAVO, flowing interval spacing, FPVO in the volcanic units, and longitudinal dispersion (BSC 2005 [DIRS 174012], Table 6-8). Transport times through the SZ are quite sensitive to parameter uncertainty associated with flowing interval properties (only uncertainty in the specific discharge scaling parameter, which is meant to account for increased specific discharge due to a wetter climate, produces a greater variation in transport times). As an example, parameter uncertainty in flowing interval spacing results in transport times that vary by several thousands of years (Arnold et al. 2000 [DIRS 166335]). The uncertainty incorporated in the horizontal anisotropy—partially a function of maximum and minimum stresses imposed on fracture and fault orientations (Faunt 1997 [DIRS 100146]; BSC 2004 [DIRS 170010], Section 6.2.6)—results in transport paths varying by several kilometers (BSC 2005 [DIRS 174012], Figure 6-6). Thus, the incorporated parameter uncertainty in fracture and fault regional properties overwhelms any changes in SZ transport times and flows paths associated with localized changes in mineral alteration.

An intruding dike could potentially affect horizontal anisotropy. The range of dike widths within the Yucca Mountain vicinity is projected to be log-normal distributed, having a minimum of 0.5 m, a mean of 1.5 m, and a 95th percentile of 4.5 m (DTN: LA0407DK831811.001 [DIRS 170768]). Relative to the large scale of the areally extensive SZ flow and transport domain (approximately 1,350 km^2), the predicted widths of the contaminant plume flow path, ranging between 100 m to 1000 m (BSC 2005 [DIRS 174012], Figure 6-6), and the relatively small dike width dimensions would cause minimal to localized changes in the hydrogeologic properties of the intruded rocks (e.g., lower permeability of the intrusion relative to the matrix of the nonwelded units). Given the scale of the SZ flow and transport model (18 km to the discharge point and the modeled 500-m model grid discretization) and the uncertainties in the flowing interval properties incorporated in *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012], Table 6-8), highly localized effects caused by igneous activity will not have significant impacts on the flux at the compliance boundary. More specifically, the large uncertainty in horizontal anisotropy modeled in the site-scale flow domain overwhelms any small scale changes in anisotropy due to future dike intrusions. As a result, localized changes in flow or transport properties due to igneous activity (inclusive of geochemical changes) will not have a significant effect on the exposure to the RMEI. A more detailed discussion of FEPs related to igneous activity is given in *Features, Events, and Processes*: *Disruptive Events* (BSC 2005 [DIRS 173981], Section 6.2.2). Therefore, changes in rock properties due to igneous activity can be excluded based on low consequence because they will not significantly change radiation exposure to the RMEI or radionuclide releases to the accessible environment.

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.4 Ash Redistribution in Groundwater (1.2.04.07.0B)

FEP Description: Following deposition of contaminated ash on the surface, contaminants may leach out of the ash deposit and be transported through the subsurface to the compliance point.

Screening Decision: Excluded–Low consequence

Screening Argument:

The probability of the disruption of the repository by igneous activity (intersection of the repository by a basaltic dike) has mean annual probability of 1.7×10^{-8} (BSC 2004 [DIRS 169989], Table 7.1). In the case when the igneous intrusion intersects the repository, there is a probability that the repository will be disrupted by an eruption as well. The probability of eruption is expressed as the annual probability that one or more eruptive conduits would form within the repository, conditional on intersection of the repository by a dike. The mean probability of this event is 1.3×10^{-8} per year (BSC 2004 [DIRS 169989], Section 7.1). The probability of such an eruption occurring, and intersecting the repository during the first 10,000 years of waste emplacement is approximately 1.3×10^{-4} (see *Supplemental Discussion* for this FEP in this SZ FEP report). If an eruption were to occur through the repository entraining radioactive waste, contaminated tephra would be deposited on the surface, and radionuclides could be leached from the contaminated tephra and be transported through the UZ and SZ to the RMEI location.

For this exercise, it is assumed six waste commercial spent nuclear fuel (CSNF) packages are entrained in the volcanic eruption, although the estimated median number of packages intersected by a single volcanic eruption intersecting one drift is slightly more than five waste packages (BSC 2005 [DIRS 174066], Section 7.2; DTN: MO0504MWDNUMWP.001 [DIRS 173521]). The conservative assumption is made that all of the waste is uniformly distributed in the ash blanket on the ground surface and that all radionuclides derived from the volcanic ash blanket are captured in the community's hypothetical pumping wells. Additionally, the glacial-transition climate scenario for the computation of the infiltration rate and fluxes is assumed since these conditions minimize the radionuclide transport time to the well. Given these imposed conditions, the resulting estimated annual dose is 4.96 mrem/year (as calculated in the *Supplemental Discussion* Table 6.2-1 for this FEP). The resulting probability-weighted annual dose due to leaching of radionuclides from contaminated ash becomes less than 6.45×10^{-4} mrem/year (as calculated in the *Supplemental Discussion* for this FEP). This is significantly less than the probability-weighted doses resulting from other igneous pathways during this period (CRWMS M&O 2000 [DIRS 153246], Section 4.2).

The effects of nonuniform distribution of the ash blanket are addressed in the following *Supplemental Discussion*. Biosphere FEPs related to exposure of the RMEI resulting from volcanic ash deposited on the soil surface are presented in *Evaluation of Features, Events, and Processes (FEP) for the Biosphere Model* (BSC 2005 [DIRS 174107]). The effects of ashfall on SZ transport are excluded on the basis of low consequence because ashfall will not significantly change radiation exposure to the RMEI or radionuclide releases to the accessible environment.

TSPA Disposition: N/A

Supporting Reports: N/A

Supplemental Discussion:

This supplemental discussion presents a simplified analysis to demonstrate the impact of contaminated radionuclide-bearing-ash deposited on the surface leaching and transporting through the UZ and SZ to the compliance point. Various assumptions associated with this analysis are presented here for completeness:

- The type of waste entrained in the volcanic eruption is CSNF.
- The radionuclide inventory in the waste packages is assumed to be the average for CSNF at the time of waste emplacement.
- The volcanic ash blanket is entirely distributed in the 18-km region between the repository and the RMEI.
- The volcanic ash is evenly distributed over the 18-km region between the repository and the RMEI.
- The radionuclides in the ash layer are entirely and immediately dissolved in the infiltrating groundwater along the 18-km flow path.
- Radionuclides are transported without radioactive decay in the SZ.
- The thickness of the UZ is assumed to be 100 m.
- Uniform, one-dimensional flow is assumed to deliver the radionuclide mass to the hypothetical pumping wells of the RMEI at a steady rate.
- The annual dose estimated for an igneous event occurring in the first year is representative of events that might occur at any time in the first 10,000 years.
- The effect of local well drawdown is considered in the averaged gradient over 18-km.
- The Glacial-transition climate infiltration rates and fluxes are assumed for transport calculations.
- Alluvial retardation coefficients are assumed over the entire transport path

For this screening analysis, the contents of six waste packages are considered to be entrained in the volcanic eruption and all of the waste resulting from the eruption is uniformly distributed in the ash blanket on the ground surface. Note that the median number of waste packages intersected by a single volcanic eruption intersecting one drift is slightly greater than five (BSC 2005 [DIRS 174066], Section 7.2; DTN: MO0504MWDNUMWP.001 [DIRS 173521]). The six waste packages are assumed to contain CSNF, which is the most common type of waste package in the repository. The radionuclide inventory in the waste packages is assumed to be the average for CSNF at the time of waste emplacement. This is equivalent to assuming that the volcanic eruption occurs immediately after waste emplacement, an assumption that conservatively maximizes the impact of short-lived radionuclides. The inventories for key radionuclides in the erupted ash are shown in Table 6.2-1. The volcanic ash blanket is assumed to be entirely distributed in the 18-km region between the repository and the RMEI. This assumption maximizes the quantity of radionuclides that is available for transport via the SZ to the community's hypothetical pumping wells. A simplifying assumption is made that the volcanic ash is evenly distributed over the 18-km region between the repository and the RMEI.

It is assumed that the radionuclides in the ash layer are entirely and immediately dissolved in the infiltrating groundwater along the 18-km flow path. It is also conservatively assumed that radionuclides are transported without radioactive decay in the SZ; however, radioactive decay is accounted for during transport from the ground surface to the water table. In addition, the conservative assumption is made that all radionuclides derived from the volcanic ash blanket are captured in the hypothetical pumping wells of the RMEI. Per requirements given in 10 CFR 63 [DIRS 173273], the same groundwater volume that is used to determine the radionuclide concentration in the TSPA-LA for groundwater and individual protection, 3,000 acre-ft (10 CFR 63, Subparts 63.312(c) and 63.332(a)(3) [DIRS 173273]), is used in this analysis to calculate concentration for evaluating dose to the RMEI.

Transport of radionuclides from the ash blanket to the water table is conceptualized to occur by one-dimensional flow downward through alluvium. The groundwater velocity in the UZ above the water table is calculated using an average volumetric moisture content of 0.1. This is a reasonable average value for vegetated native soil in the region (Johnson et al. 2002 [DIRS 165069], Figure 16) and is likely lower than what would occur under washes in which intermittent infiltration occurs. The calculation of groundwater velocity also uses an infiltration flux of 2.21 mm/year, which is the estimated recharge rate along Fortymile Wash in the upper Jackass Flats reach (BSC 2004 [DIRS 170015], Table 6-3). To minimize the travel time through the UZ and SZ this infiltration flux is scaled by 3.9 which represents the SZ groundwater flux ratio used for the glacial-transition climate change (BSC 2005, [DIRS 174012], Table 6-5). This results in an infiltration flux of 8.62 mm/yr. In addition, the thickness of the UZ is assumed to be 100 m, which is an approximate value in the region near the hypothetical pumping wells, based on the depth to the water table in well NC-EWDP-19P (DTN: GS010908312332.002 [DIRS 163555]). The average transport time from the ground surface to the water table for radionuclides is calculated as:

$$t = R_f \frac{z\theta_m}{q} \quad \text{(Eq. 6-1)}$$

where t is the average transport time [T], R_f is the retardation factor in the alluvium [dimensionless], z is the depth to the water table [L], θ_m is the moisture content [dimensionless], and q is the recharge flux [L/T]. The retardation factor for flow in the UZ is defined by Freeze and Cherry (1979 [DIRS 101173], p. 404) as:

$$R_f = 1 + \frac{\rho_b K_d}{\phi} \tag{Eq. 6-2}$$

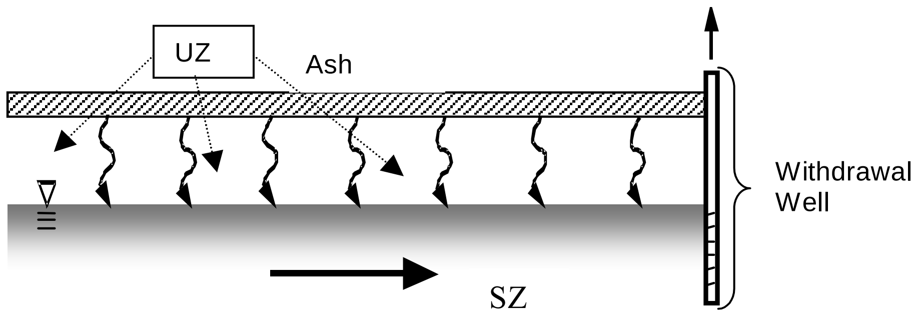
where ρ_b is the dry bulk density of the alluvium [M/L^3], K_d the sorption coefficient (which is the ratio of the contaminant mass in a unit volume of solution per contaminant mass sorbed on a unit mass of solid) [L^3/M], and ϕ is the total porosity of the alluvium [dimensionless]. The value of bulk density used in the analysis is 1.91 g/mL and the porosity is 0.3, which are the expected values (BSC 2005 [DIRS 174012], Table 6-8). The median values for the sorption coefficients for the radionuclides, as taken from *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012], Table 6-8), are shown in Table 6.2-1. Radionuclides will experience radioactive decay during transport in the UZ to the water table. The remaining activity of radionuclides after transport through the UZ, which can be derived from Domenico and Schwartz (1990 [DIRS 100569], Equation 14.11), is:

$$A = A_0 (2^{-t/T_{0.5}}) \tag{Eq. 6-3}$$

where A is the activity at the water table [Curies], A_0 is the activity in the ash [Curies], $T_{0.5}$ is the half-life of the radionuclide, and t is the average transport time. Substituting Equations 6-1 and 6-2 into Equation 6-3 yields the activity of each radionuclide at the water table in Curies.

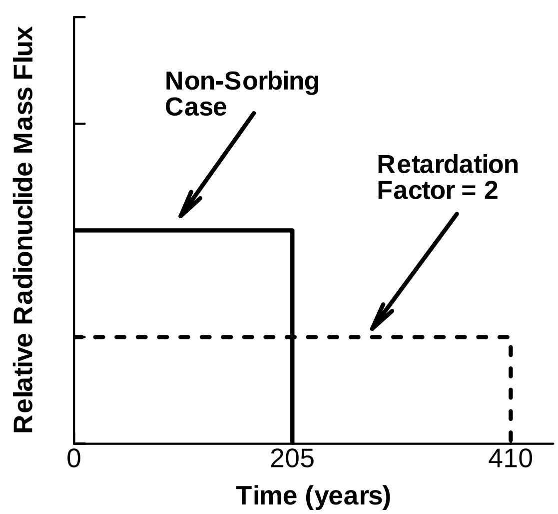
Note that the isotopes of plutonium and americium are treated as irreversibly attached to colloids in the analysis presented here. Consequently, the retardation factor used is the median value for the retardation factor of colloids in alluvium (BSC 2005 [DIRS 174012], Table 6-8). Radionuclides irreversibly attached to colloids migrate more rapidly than radionuclides reversibly attached to colloids, so this assumption is conservative with regard to estimated dose.

The SZ is conceptualized as a simplified one-dimensional flow system between the repository and the accessible environment, as shown in Figure 6.2-1. In the simplified conceptual model of radionuclide transport in the SZ, uniform, one-dimensional flow is assumed to deliver the radionuclide mass to the hypothetical pumping wells of the RMEI at a steady rate. An approximate transport time of 205 years for a nonsorbing species from the water table located just below the repository footprint is taken from the analysis of SZ transport using the three-dimensional SZ transport abstraction model (BSC 2005 [DIRS 174012], Figure 6-28) under glacial-transition climatic conditions. In contrast, the median transport time under present day climate conditions is 800 years (BSC 2005 [DIRS 174012], Figure 6-28). The estimated transport time of 205 years is derived by scaling the 800 year transport time by the SZ groundwater flux ratio for glacial-transition climate (BSC 2005, [DIRS 174012], Table 6-5). A simplifying assumption is made that radionuclides are transported through the UZ uniformly. The resulting idealized radionuclide mass breakthrough curve (BTC) is shown in Figure 6.2-2. Note that the first radionuclide mass is released to the accessible environment at the time of first arrival at the water table (shown as time zero in Figure 6.2-2). The duration of the BTC is 205 years under glacial-transition conditions, at which time the most upstream of the radionuclide mass arrives. The average (and also peak) concentration of the nonsorbing radionuclide in the water supply of the hypothetical farming community is calculated by dividing the total radionuclide mass delivered to the SZ from the contaminated ash by the water usage over the 205 years. For those radionuclides that experience sorption and retardation in the SZ, the distribution of radionuclide mass arrival at 18-km is spread over a longer period of time, as indicated by the example shown in Figure 6.2-2. A retardation factor of two means that the arrival of radionuclide mass at 18-km is spread over approximately 410 years, and the radionuclide mass flux is one-half of that for the nonsorbing species.



NOTE: SZ = Saturated Zone; UZ = Unsaturated Zone.

Figure 6.2-1. Schematic Cross Section Diagram of Simplified One-Dimensional Model for Transport in the SZ of Radionuclides Leached from Volcanic Ash



NOTE: For illustration purposes only.

Figure 6.2-2. Example of Idealized Radionuclide Mass BTCs at 18-km Distance Resulting from Volcanic Ash Leaching for Nonsorbing and Sorbing Radionuclides

The estimate of annual dose from this simplified analysis is shown in Table 6.2-1. An explanation on how this estimate was obtained is provided below.

The conversion from mass of radionuclide in a waste package to the activity can be accomplished by multiplying the mass by the specific activity of a given radionuclide. Specific activity can be calculated as a product of the number of atoms of a radionuclide in a unit mass (here one gram) $\frac{Av}{AW}$ and the radioactive decay constant $\frac{\ln(2)}{T_{1/2}}$ (Cember 1983 [DIRS 108074], pp. 71 to 74).

$$A_{WP,CSNF} = m \times \frac{Av}{AW} \times \frac{\ln(2)}{T_{1/2}}$$

where

$A_{WP,\ CSNF}$	=	activity of a given radionuclide in CSNF waste package (Bq)
m	=	radionuclide mass per waste package, g
Av	=	Avogadro's number (6.022×10^{23} atoms/mole)
AW	=	atomic weight of radionuclide under consideration
$T_{1/2}$	=	radionuclide half-life, s

To convert from Bq to Ci, the value calculated using the above equation needs to be divided by 3.7×10^{10}.

The representative volume of water for each radionuclide is calculated as the product of the expected annual groundwater usage, the 205-year transport time, and the retardation factor. The concentration is calculated by dividing the activity of the radionuclide at the water table by the representative water volume. The expected annual dose is calculated as the product of the average concentration and the biosphere dose conversion factor for each radionuclide, as shown in Table 6.2-1.

The resulting estimated conditional total annual dose assuming glacial-transition climatic conditions is 4.96 mrem/year. As shown in Table 6.2-1, the calculated annual dose from shorter-lived radionuclides (e.g., ^{90}Sr and ^{137}Cs) is zero due to decay during transport to the water table following leaching from the ash layer. Only ^{99}Tc, ^{129}I, and ^{14}C, contribute to the total calculated dose. These are the only radionuclides included in the total dose calculation because the other radionuclides arrive at the SZ after 10,000 years as shown in Table 6.2-1. A similar calculation assuming present day climatic conditions gives a conditional total annual dose of 1.34 mrem/year. This conditional annual dose should be weighted by the probability of the occurrence of a volcanic eruption to evaluate its potential impact on the overall exposure to RMEI. Volcanic eruptions at Yucca Mountain are unlikely; *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* (BSC 2004 [DIRS 169989], Table 7.1) concludes that the mean annual frequency of igneous intrusion into the repository footprint is 1.7×10^{-8}. The probability of eruption, conditional on an intrusion, is less, 1.3×10^{-8} (not all hypothetical igneous intrusions would result in an eruption at the repository). Adopting the 1.3×10^{-8} per year value and assuming that future igneous activity at Yucca Mountain is a Poissonian process, there is approximately a 1.3×10^{-4} probability of an eruptive igneous event at Yucca Mountain in the next 10,000 years. This event is equally likely to occur in any year during the 10,000-year period, and the probability that the event has already occurred (and that groundwater is contaminated) rises from 1.3×10^{-8} in the first year to 1.3×10^{-4} after 10,000 years.

A rigorous approach to estimating the probability-weighted dose through time would require evaluating consequences of events at each year and summing the probability-weighted doses, as done in the TSPA for site recommendation for doses incurred by direct exposure to a contaminated ash layer (CRWMS M&O 2000 [DIRS 153246], Section 4.2). However, it is conservative to assume that the annual dose estimated for an igneous event occurring in the first year is representative of events that might occur at any time in the first 10,000 years. In fact, the first-year event provides an upper bound on the radionuclide inventory available for later events. The probability of an eruptive igneous event occurring during the first 10,000 years is 1.3×10^{-4}, which yields a probability-weighted annual dose of approximately 6.45×10^{-4} mrem/year for leaching of radionuclides from contaminated ash and contamination of the groundwater used by the RMEI. This is significantly less than the probability-weighted doses resulting from other igneous pathways during this period of about 0.08 mrem/year (CRWMS M&O 2000 [DIRS 153246], Section 4.2). Although the analyses of the igneous expected annual dose are being reevaluated for the TSPA-LA, it is unlikely that the conditional dose from leaching of contaminated ash would be a significant contributor to simulated annual dose, particularly considering the conservative nature of the simplified analysis presented here.

One assumption of the simplified analysis summarized in Table 6.2-1 is that the blanket of ash is uniformly deposited on the ground surface above the aquifer. A plausible alternative scenario is that the ash could be redistributed, for example, by running water in Fortymile Wash before leaching of radionuclides. A thicker deposit of ash in one area would lead to higher concentrations of radionuclides in that area of the SZ and consequent higher peak annual dose from the production of contaminated groundwater. The increase in the estimated peak annual dose would be approximately proportional to the increased thickness of the ash deposit relative to the average thickness due to erosional and depositional processes. In other words, if the ash deposit were redistributed such that it was five times thicker at the downstream end of Fortymile Wash relative to the average ash thickness, then the peak annual dose would be about five times greater. This would be a significant increase relative to the estimated conditional annual dose of 4.96 mrem/year. However, considering the probability weighting presented above and the numerous conservative simplifying assumptions used in the analysis, this aspect of ash redistribution has low consequence to repository performance.

In conclusion, leaching from radionuclide-laden ash fall is excluded from the SZ on the basis of low consequence because it will not significantly change radiation exposure to the RMEI or radionuclide releases to the accessible environment.

Table 6.2-1. Screening Estimate of Dose from the SZ for Leaching from Volcanic Ash, Conditional on Eruptive Release

Radio-nuclide	Activity per Package[a] (Ci)	Activity Released[a] (Ci)	Expected K_d (mL/g)[b]	Expected R_f	Half-Life [d] (years)	SZ Arrival Time (yrs)	Curies at Water Table (Ci)	Water Volume (L)[g]	Concentration (pCi/L) [f]	BDCF (mrem/year per pCi/L)[c]	Annual Dose (mrem/year)[h]
^{14}C	6.13E+00	3.68E+01	0.0	1.0	5.73E+03	1.16E+03	3.20E+01	7.62E+11	4.19E+01	9.02E-03	3.79E-01
^{90}Sr	3.44E+05	2.06E+06	210.0	1338.0	2.91E+01	1.55E+06	0.00E+00	1.02E+15	0.00E+00	1.14E-01	0.00E+00
^{99}Tc	1.30E+02	7.78E+02	0.0	1.0	2.13E+05	1.16E+03	7.75E+02	7.62E+11	1.02E+03	3.41E-03	3.47E+00
^{129}I	3.08E-01	1.85E+00	0.0	1.0	1.57E+07	1.16E+03	1.85E+00	7.62E+11	2.43E+00	4.58E-01	1.11E+00
^{137}Cs	5.19E+05	3.12E+06	728.0	4635.9	3.00E+01	5.38E+06	0.00E+00	3.53E+15	0.00E+00	3.58E-01	0.00E+00
^{232}U	2.20E-01	1.32E+00	4.6	30.3	7.20E+01	3.51E+04	0	2.31E+13	0.00E+00	2.64E+00	0.00E+00
^{233}U	5.63E-04	3.38E-03	4.6	30.3	1.59E+05	3.51E+04	2.90E-03	2.31E+13	0.00E+00	5.73E-01	0.00E+00
^{234}U	1.10E+01	6.62E+01	4.6	30.3	2.45E+05	3.51E+04	6.00E+01	2.31E+13	0.00E+00	3.77E-01	0.00E+00
^{236}U	2.52E+00	1.51E+01	4.6	30.3	2.34E+07	3.51E+04	1.51E+01	2.31E+13	0.00E+00	3.21E-01	0.00E+00
^{238}U	2.66E+00	1.60E+01	4.6	30.3	4.47E+09	3.51E+04	1.60E+01	2.31E+13	0.00E+00	3.46E-01	0.00E+00
^{237}Np	3.27E+00	1.96E+01	6.4	41.7	2.14E+06	4.84E+04	1.93E+01	3.18E+13	0.00E+00	1.13E+00	0.00E+00
^{238}Pu	2.64E+04	1.58E+05	N/A	34.0	8.77E+01	3.94E+04	0	2.59E+13	0.00E+00	1.95E+00	0.00E+00
^{239}Pu	2.71E+03	1.63E+04	N/A	34.0	2.41E+04	3.94E+04	5.23E+03	2.59E+13	0.00E+00	5.13E+00	0.00E+00
^{240}Pu	4.73E+03	2.84E+04	N/A	34.0	6.54E+03	3.94E+04	4.34E+02	2.59E+13	0.00E+00	4.95E+00	0.00E+00
^{241}Am	2.84E+04	1.71E+05	N/A	34.0	4.32E+02	3.94E+04	0	2.59E+13	0.00E+00	2.61E+00	0.00E+00
^{243}Am	2.52E+02	1.51E+03	N/A	34.0	7.38E+03	3.94E+04	3.72E+01	2.59E+13	0.00E+00	4.28E+00	0.00E+00
							Total	estimated	conditional	dose	4.96E+00

NOTE: The probability of eruptive release of radionuclides is about 1.3 x 10^{-8}/year (BSC 2004 [DIRS 169989], Table 7-1).
[a] Source: SN0310T0505503.004, spreadsheet: invdtnj.xls [DIRS 168761].
[b] Source: BSC 2005 [DIRS 174012]), Table 6-8. Note, Pu and Am are modeled as irreversibly attached to colloids. See Table 6-8 (BSC 2005, [DIRS [174012] for irreversible colloid retardation factors.
[c] Source: DTN: MO0501MWDBDCFS.000. [DIRS 172835] BDCFs for Glacial-transition Climate
[d] Source: Eckerman and Ryman 1993 [DIRS 107684], Table A-1.
[e] Estimated conditional annual dose.
[f] Concentration is a function of the water volume at 10,000 years.
[g] Water volume is the product of expected annual groundwater usage, the 205-year transport time, and the retardation factor.
BDCF = biosphere dose conversion factor
[h] Annual total dose for 10,000 years

6.2.5 Hydrothermal Activity (1.2.06.00.0A)

FEP Description: Naturally-occurring high-temperature groundwater may induce hydrothermal alteration of minerals in the rocks through which the high-temperature groundwater flows.

Screening Decision: Excluded–Low consequence

Screening Argument:

The presence of silica, calcite, and clay vein deposits and mineral replacement assemblages indicate the presence of past hydrothermal activity associated with both silicic volcanism and caldera and basaltic volcanism within the Basin and Range province. Evidence of hydrothermal mineral alteration is seen in the Calico Hills, Claim Canyon, and along the south flank of Shoshone Mountain (BSC 2004 [DIRS 170037] Table 6-17, Figure A6-3); all three past hydrothermal areas are not along the SZ flow path and lie north and northeast of Yucca Mountain (BSC 2004 [DIRS 170037], Figure A6-3). Yucca Mountain is located outside the caldera margin that encompasses Claim Canyon and Shoshone Mountain; hence, it was never near this ancient hydrothermal source (BSC 2004 [DIRS 170037], Figure A6-3). None of the three past hydrothermal areas are along the SZ flow path from the repository to the RMEI, and all three areas lie north and northeast of Yucca Mountain.

The likelihood of future hydrothermal activity to develop within the vicinity of SZ flow paths is conditioned to future volcanic and igneous activity. Volcanic activity and igneous intrusions in the areally extensive Yucca Mountain region, once extensive in nature, are now in a relatively quiescent phase (BSC 2004 [DIRS 169989], Section 6.2). Silicic volcanism was dominant in the region between 11 and 15 Ma. Plate extension and an episode of major caldera formation occurred between 13 and 9 Ma in the Great Basin region (Sawyer et al. 1994 [DIRS 100075], Figure 4). Crustal extension rates started to decline about 13 Ma. This progression in crustal evolution resulted in silicic volcanism being replaced with basaltic volcanism. Basaltic volcanism within the Yucca Mountain region commenced during the later part of the caldera-building phase, around 9 Ma. Postcaldera building basaltic igneous activity within Yucca Mountain peaked approximately 7 Ma and is now in a declining state. These intruding dikes could induce alteration of the in situ mineralogy adjacent to the intruded rock (i.e., the contact zone). Future igneous activity within the Crater Flat basin will typically cause minimal, highly localized basaltic dike-like intrusions with average widths on the order of one meter (CRWMS M&O 1996. [DIRS 100116], Section 3.2.3). Therefore, mineral alteration in this contact zone will be minimal. This is supported by investigations at the Grants Ridge analogue site, which indicates that basaltic intrusion produced only localized formation of volcanic glass within the contact zone (CRWMS M&O 1998 [DIRS 105347], Section 5, p. 74). Investigations of basaltic intrusions at Paiute Ridge (Carter Krogh and Valentine 1996 [DIRS 160928], pp. 7 to 8) suggest that igneous activities altered rock properties to only a few tens of centimeters to, at most, a meter perpendicular to an intruding dike. Associated hydrothermal activity is conditioned to these localized igneous events.

Studies of two-phase fluid inclusions in the UZ at Yucca Mountain using petrography, microthermometry, and uranium-lead dating indicate that temperatures have remained close to the current ambient values over the past two to five million years (Wilson et al. 2003 [DIRS 163589], Section 8). These findings show that significant or widespread hydrothermal activity has not occurred in the UZ in the recent geologic past, and suggest that hydrothermal activity has been absent from the nearby SZ.

Radionuclide transport processes in the SZ could potentially be impacted by intrusion of igneous dikes by the alteration of sorption characteristics of the tuff aquifer. These alterations could include mineralogical changes and changes of sorption coefficient values in response to elevated temperatures. As noted above, mineralogical changes would be localized around potential future igneous intrusions and would not affect a significant portion of the entire volume of the tuff aquifer within the SZ. Elevated temperatures near dikes would also be localized and data on SZ sorption coefficients indicate little statistical variation for temperatures up to 80ºC (BSC 2004 [DIRS 170036], Appendix A1).

Given the lack of evidence of any past hydrothermal activity along the Crater Flat basin (BSC 2004 [DIRS 170037], Appendix A, Figure A6-3), coupled with the relatively small widths of igneous intrusions that would intersect the SZ flow domain and small interfacial zone where the in situ rock's mineralogy is thermally altered, it is inferred that any associated hydrothermal activity produced from future igneous activity will be localized and of low consequence to the long term and regional SZ flow paths. In summary, hydrothermal activity is excluded based on low consequence, because it will not significantly change radiation exposure to the RMEI or radionuclide releases to the accessible environment.

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.6 Large-Scale Dissolution (1.2.09.02.0A)

FEP Description: Dissolution can occur when any soluble mineral is removed by flowing water. Large-scale dissolution is a potentially important process in rocks that are composed predominantly of water-soluble evaporite minerals, such as salt.

Screening Decision: Excluded–Low consequence

Screening Argument:

The hydrogeologic framework model, which is based on the available geologic information from the Yucca Mountain region (D'Agnese et al. 1997 [DIRS 100131]; BSC 2005 [DIRS 174109], Figures 6-1 and 6-7), uses 19 hydrogeologic units to represent the geologic system. Of these hydrogeologic units, the carbonates are the most soluble in groundwater (solubility of 90 mg/L to 500 mg/L, depending on the $p_{CO2,}$ at 1 atm pressure and 25°C (Freeze and Cherry 1979 [DIRS 101173], p. 106), and the permeability of these units is primarily due to solution channels and fractures. The transport pathways in the SZ are primarily through volcanic tuffs and alluvial material (BSC 2004 [DIRS 170037], Section 6.6.2.3), which largely consists of disaggregated tuffaceous rocks (BSC 2004 [DIRS 170036], Appendix A, Section A7.1.3). The carbonate units are included in the SZ flow and transport model, and the assigned permeabilities are representative of the existing solution channels and fractures. The carbonate units along the SZ transport pathways are located well below the water table (BSC 2005 [DIRS 174109], Figures 6-1 and 6-18) along the SZ flow path. New extensive dissolution cavities are unlikely to develop at depths well below the water table where CO_2 has been depleted. Even if they did form, there would be no detrimental effect on the simulated performance of the site, as transport occurs near the water table in the upper volcanic, lower volcanic, and alluvial aquifers (BSC 2004 [DIRS 170037], Section 6.6.2.3).

The volcanic rocks present at the water table are not readily soluble in water; their solubility is low enough that large-scale dissolution does not occur. Volcanic rocks tend to weather to clay minerals with a relatively small amount of silica going into solution. The volcanic units in the vicinity of Yucca Mountain are primarily comprised of silica (quartz and cristobalite), alkali feldspars, and zeolites (BSC 2004 [DIRS 170036], Appendix A, Section A2). The solubility of quartz is 12 mg/L at 1 atm pressure and 25°C (Freeze and Cherry 1979 [DIRS 101173], p. 106), and is relatively low compared to evaporites and carbonate solubilities.

Given unusually drier climatic conditions, the water table may drop to lower levels from its current potentiometric surface. While unlikely, there is mineralogical evidence that the maximum decline in the water table from current levels could be at most 300 m (see FEP 1.3.07.01.0A–Water table decline). This potential decline still retains the water table several hundreds of meters above the carbonate aquifer along the simulated SZ transport paths (BSC 2005 [DIRS 174109], Figures 6-1 and 6-18).

Anthropogenic water table declines within the Yucca Mountain vicinity have been insignificant. In the Jackass Flats hydrographic basin, current groundwater withdrawal rates and their effects on water table elevations are insignificant (La Camera et al. 1999 [DIRS 103283], pp. 17 through 22; Young 1972 [DIRS 103023]). Based on these observations, it is concluded that future withdrawal rates will not cause the water table to drop along the transport paths to the more soluble carbonate units. Transport of radionuclides will primarily take place in the relatively insoluble volcanic units located near the surface of the water table and well above the more soluble carbonate units where large-scale dissolution could take place. Additionally, large-scale dissolution can be excluded from the SZ flow and transport models because evaporites, in particular halite with a solubility of 360,000 mg/L at 1 atm pressure and 25°C (Freeze and Cherry 1979 [DIRS 101173], p. 106), are not dominant minerals in the formations along the simulated transport pathways. In conclusion, large-scale dissolution is excluded based on low consequence because it will not significantly change radiation exposure to the RMEI or radionuclide releases to the accessible environment.

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.7 Hydrologic Response to Seismic Activity (1.2.10.01.0A)

FEP Description: Seismic activity, associated with fault movement, may create new or enhanced flow pathways and/or connections between stratigraphic units, or it may change the stress (and therefore fluid pressure) within the rock. These responses have the potential to significantly change the surface and groundwater flow directions, water level, water chemistry, and temperature.

Screening Decision: Excluded–Low consequence

Screening Argument:

Within the Basin and Range Province (which includes the Yucca Mountain region), peak extensional stresses occurred between 10 and 12 Ma with extension rates between 10 and 30 mm/year (National Research Council 1992 [DIRS 105162], Chapter 2). These rapid extension rates formed two major north trending extension belts and normal faulting zones. Approximately 5 Ma, the rate of regional extension declined to 5 to 10 mm/year; extension rates are still in a declining state today (National Research Council 1992 [DIRS 105162], Chapter 2). It is the extensional stresses imposed on the areally broad Basin and Range Province that impart the extension, compression, and shear stresses on the crust, and determine seismic activity that can produce faults, fault slip, fracture formation, and fracture connectivity. The type of stress transmitted locally is dependent on location, depth, and juxtaposition of existing faults and fractures. These locally imposed stresses, which control existing hydrological properties (BSC 2004 [DIRS 170037], Section 6.3.2.10), are driven by the crustal (and now declining) extension rates. Release of stress results in seismic activities that create vibratory motion, faults (rupture), fault displacement, or areal redistribution of stresses not associated with specific faults. Vibratory stresses caused by seismic activity can alter the hydrologic properties of the parent rock. A seismic event can permanently affect rock hydrologic properties by (1) causing a change in pore pressure, which is usually a product of regional stress changes, or (2) an increase or decrease in permeability produced by either dilation, compression, or breakage of granular structures produced from dynamic ground motion.

A seismic event is most likely to cause movement along existing faults, rather than developing new faults (BSC 2005 [DIRS 173981], Section 6.2.1.10), or change rock and inter-granular stresses, thus, affecting rock hydrologic properties due to the creation of brecciation and gouge zones adjacent to the faults and existing fractures, and possibly the production of new fractures (outside of the brecciated zone). Long-term changes in water table elevations are associated with seismically induced permanent changes in pore pressure and volume strain or permanent changes in regional permeability. A transient change in water table elevations is associated with the passage of a seismically perturbed surface wave that passes through the region. Water table elevations can change from a few centimeters to several tens of meters in response to seismic activity. The change in water table elevation can also affect (1) SZ flow and pathways, if the change in water table elevations are extensive enough to change the regional potentiometric surfaces, and (2) groundwater geochemistry, as the displaced water is moved into, and interacts with, rocks composed of different mineralogy. Because seismic activity is closely associated with tectonic activity, a decline in tectonic activity coincides with a decline in the frequency and intensity of seismic activity.

Investigations of analogue sites and numerical studies demonstrate future seismic activity within the Yucca Mountain region will not change long-term (i.e., over 10,000 years) regional SZ groundwater flow patterns, water chemistry, and temperatures. A brief summary of these investigations is given below.

Expert elicitation, documented in the Probabilistic Seismic Hazard Analysis (PSHA) report (CRWMS M&O 1998 [DIRS 103731], Sections 4 and 8), provides information that can be used to assess the effects of a seismic event on the hydrologic properties of faults and the host rock. As part of the PSHA, six teams of experts evaluated the available data to assess the fault displacement potential for 9 sites that represent the range of fault conditions in the Yucca Mountain vicinity (CRWMS M&O 1998 [DIRS 103731], Figure 4-9). The teams also characterized the uncertainty in their assessment by defining alternative models and approaches and assigning them weights. For each combination of alternatives, results for each site were provided as the annual frequency with which given levels of fault displacement would be exceeded. Uncertainty in the results was characterized by calculating the mean hazard and various percentile values. Results for each team were then combined using equal weights to determine the integrated fault displacement hazard.

For the area between the Solitario Canyon and the Ghost Dance faults, fault displacement hazard for intact rock is less than 0.1 cm for a 1×10^{-8} annual exceedance probability (CRWMS M&O 1998 [DIRS 103731], Section 8.2.1). This area is along the predicted transport pathway between the repository and the 18-km boundary. Given this small predicted displacement, it is inferred no significant new faults and fractures, which would have the potential to create new flow paths or significantly change the existing flow paths and flow directions, are expected in the intact host rock.

Because it is unlikely a seismic event will create new faults (CRWMS M&O 1998 [DIRS 103731], Section 8.2.1), movement along existing faults is of primary interest. Excluding the Solitario Canyon and Bow Ridge faults, the range of the expert teams' results for intrablock fault displacement, taking into account alternative approaches, is approximately 0.1 – 4.5 m at an annual-exceedance probability of 1×10^{-8} (CRWMS M&O 1998 [DIRS 103731], Figures 8-17 to 8-27). This is taken as an upper limit for intrablock faults within the Yucca Mountain region. Incorporating the weights for each team's alternative approaches and combining the results for all six teams using equal weight, the 'integrated' mean displacement hazard varies from less than 0.1 m to approximately 2.5 m (CRWMS M&O 1998 [DIRS 103731], Figures 8-4 to 8-12). The mean fault displacements, at an annual-exceedance probability of 1×10^{-8}, for the Drill Hole Wash, Ghost Dance, Sundance faults and a fault west of Dune Wash is bounded by 2.4 m (CRWMS M&O 1998 [DIRS 103731], Figures 8-4 to 8-7).

The exceptions to this displacement range are the predicted displacements for the Solitario Canyon and Bow Ridge faults (CRWMS M&O 1998 [DIRS 103731], Sites 2 and 1 in Figure 4-9), which are block-bounding faults and are expected to have higher displacements. The mean fault displacement, at an annual-exceedance probability of 1×10^{-8}, for these block-bounding faults are approximately 13 m along the Solitario Canyon fault (CRWMS M&O 1998

[DIRS 103731], Figure 8-3) and approximately 6 m along the Bow Ridge fault (CRWMS M&O 1998 [DIRS 103731], Figure 8-2).

Based on the PSHA results, fault displacements with a 1×10^{-8} annual probability of exceedance are not expected to create new flow paths or significantly alter predicted SZ flow paths. Several investigations have been conducted to estimate the hydrologic response (i.e., change in water table elevations) given predicted fault displacements. One investigation was performed by the National Research Council (1992 [DIRS 105162], Chapter 5). This group estimated the maximum changes in water table elevations over a 10,000-year period in response to seismic activity, which presumes some degree of fault displacement. They estimated fault displacement using two modeling approaches: (1) a dislocation approach, where zones of extension on one side of a fault are balanced by compression across the fault; and (2) the more realistic 'changes in the regional stress' approach caused by normal fault slippage in regions of extension. The regional stress approach evaluated the effect of stress on pore pressure, which is dependent on the elastic properties of the bulk rock and the mineral grains. Both models resulted in a transient change in water table elevation given a seismic event in the Yucca Mountain region. However, the extent of the rise differed for both models. Adopting the dislocation model, the maximum rise in the water table is approximately 13 m. Results from the regional stress approach resulted in a maximum water table rise of 50 m. The later approach assumes realistically conservative rock and mineral elastic properties. The panel concluded that regardless of which approach is taken, the maximum water table rise given a seismic event would be less than 50 m. Given the National Research Council's study, it is inferred that a 13 m slip along Solitario Canyon fault, which could implicitly impose the maximum change in volume stress strain changes on pore pressure, would result in no more than a 50-m rise in the water table (see related FEP 2.2.06.02.0A–Seismic activity changes porosity and permeability of faults).

Several other numerical studies estimate the hydrologic response due to fault displacement. Analysis performed by Gauthier et al. (1996 [DIRS 100447], pp. 163 to 164) indicates that the greatest strain-induced changes in water table elevation occur with strike-slip faults. Simulations of the timing, magnitude, and duration of water table rise indicate a maximum rise of 50 m within an hour of the simulated event. The simulated system returns to steady-state conditions within six months. Gauthier et al. (1996 [DIRS 100447]) concluded that:

> In general, seismically induced water table excursions caused by poroelastic coupling would not influence the models presently being used to determine long-term performance of a repository at Yucca Mountain; therefore, they were excluded from the total-system simulations.

The magnitude and transient nature of the simulated, seismically induced water table rise is consistent with other estimates and observations. Numerical simulations performed by Carrigan et al. (1991 [DIRS 100967]) modeled tectonohydrologic responses based on an earthquake associated with a 1 m fault slip. Simulation results predicted a simulated water table rise of 2 m to 3 m for a water table 500 m below ground surface. Extrapolation to a more hypothetical event of a 4 m slip results in a transient rise of 17 m near the fault (Carrigan et al. 1991 [DIRS 100967], p. 1159).

Investigations focusing on the potentiometric hydrologic response, given changes in rock properties adjacent to a fault, demonstrate that the changes in water table elevation are transient and local in nature. This type of hydrologic response is commonly referenced as seismic pumping. One such investigation was performed by Carrigan et al. (1991 [DIRS 100967]). They modeled a 100-m-wide fracture zone centered on a vertical fault, such that vertical permeability was increased by three orders of magnitude. Model results indicate a transient water table rise of up to 12 m in the fracture zone given 1 m of fault slip. The above results indicate changes in permeability along faults due to fault slippage would produce a short-term and transient seismic pumping event and would not change regional flow directions or flow paths over the 10,000-year time scale. Results from the above investigations indicate the hydrologic response due to fault displacement (i.e., changes in the water table elevation) from predicted seismic events within the Yucca Mountain region will be transient and local in nature.

Observed changes in water table elevation, given recorded seismic events, support the conclusions drawn from the above numerical studies. O'Brien (1993 [DIRS 101276]) analyzed water level fluctuations at Yucca Mountain due to earthquakes in the region. Water table fluctuations range from 90 cm associated with a 7.5 magnitude earthquake near Landers, California (approximately 420 km from Yucca Mountain) to 20 cm for a second quake of 6.6 magnitude near Big Bear Lake, California (approximately 400 km from Yucca Mountain). More notably, a 5.6 magnitude quake at Little Skull Mountain (approximately 23 km from Yucca Mountain) resulted in a maximum water table fluctuation of 40 cm. Water levels in another well declined approximately 50 cm over the three days following the earthquake; this well returned to prequake levels over a period of about six months. These observations indicate changes in the water table due to seismic events in the outlying vicinity are relatively minor and transient in nature.

A seismic event can alter in situ rock hydrologic properties along a relatively narrow zone adjacent to the fault, labeled herein as a "zone of alteration." The zone of alteration can be on the order of a few meters to tens of meters wide adjacent to the fault (see FEPs 2.2.06.01.0A-Seismic activity changes porosity and permeability of rock and 2.2.06.02.0A-Seismic activity changes porosity and permeability of faults). The existing rock properties along these zones of alteration are the cumulative product of an active seismic past regionally imposed on the Basin and Range Province over many millennia. Given the predicted lower frequencies of future seismic events, it is inferred that hydrologic properties in these zones of alteration will not be significantly altered. (Detailed discussions on the effects of seismic events on rock properties are provided in *Features, Events, and Processes: Disruptive Events* (BSC 2005 [DIRS 173981], Sections 6.2.1.8 to 6.2.1.11.)

Furthermore, flow and transport in the SZ is dominated by fault orientation and existing fractures, fracture clusters and fracture spacing, collectively labeled as flowing intervals in the SZ flow and transport model abstraction (BSC 2005 [DIRS 174012], Section 6.5.2.4). The SZ flow and transport model abstraction evaluates uncertainties assigned to flowing interval properties such as horizontal anisotropy in permeability (HAVO), flowing interval spacing (FISVO), flowing interval porosity in the volcanic units (FPVO), and longitudinal dispersion (BSC 2005 [DIRS 174012], Table 6-8). Transport times through the SZ are quite sensitive to parameter uncertainty associated with flowing interval properties (only uncertainty in the specific discharge scaling parameter, which primarily accounts for increased specific discharge due to a wetter climate, produces a greater variation in transport times). As an example, parameter uncertainty in flowing interval spacing results in transport times that vary by several thousands of years (Arnold et al. 2000 [DIRS 166335]). The uncertainty incorporated in the horizontal anisotropy (which accounts for maximum and minimum stresses imposed on faults and fracture clusters and their orientation) results in transport paths that vary by several kilometers (BSC 2005 [DIRS 174012], Figure 6-6). Thus, the incorporated parameter uncertainty for fracture and fault properties, on a regional scale, overwhelms any transient changes in SZ transport times and flows paths, given a localized change in rock properties residing in the zone of alteration.

Additionally, the evolution of the calibration and validation of the base-case flow field is based on parameter uncertainty and model sensitivity to grid discretization. The calibration process includes (1) partially varying multiple flow and transport parameters such as permeability, porosity, anisotropy, faults and fault zones, and the orientation and nature of faults to measured and interpolated water levels; and (2) sensitivity of the calibrated parameters to grid size and grid resolution (BSC 2004 [DIRS 170037], Sections 6.5.3.2, 6.6.1, and 7.0). Grid resolution is based on systematically running the model using grids of differing resolutions (increased or decreased grid discretizations in both the horizontal and vertical direction), then comparing results. The grid considered suitable for stochastic modeling is one that produces minimal differences in the model results compared to results from a grid with increased (i.e., more refined) discretization. Given this exercise, the appropriate grid discretization used in the SZ flow and transport model is one using 500 m uniformly spaced grid blocks in the horizontal direction, and 10 m to 550 m nonuniformly spaced grid blocks in the vertical direction. On a regional and long-term scale, the transient hydrologic response due to seismically-induced changes in the relatively small and discrete "zones of alteration" is insignificant due to grid discretization, coupled with model scale and the parameter uncertainty incorporated into the SZ model. (Seismic effects on rock properties adjacent and within faults and zones are discussed in FEP 2.2.06.02.0A–Seismic activity changes porosity and permeability of faults.)

Lastly, the effect of a seismically-induced hydrologic response on SZ groundwater chemistry will be insignificant. Groundwater isotopic and geochemical signatures within the Yucca Mountain region are indicative of groundwater flow directions and flow paths that have existed over the past 10,000 years. Uncorrected groundwater ages determined from carbon-14 (percent modern carbon) data (DTN: MO0012MAJIONIS.000 [DIRS 153679], Table S00453_001) and an exponential decay relationship (BSC 2004 [DIRS 170037] equation A6-3) range from about 10,000 to 16,000 years old in the vicinity of Yucca Mountain. therefore the SZ groundwater under the repository and along the SZ transport path is paleoclimate recharge water. Flow and transport modeling results show good history matching with the geochemical-modeled flow patterns and deduced mixing relations using hydrochemical and isotopic data (BSC 2004 [DIRS 170037], Figures 6-43 and A6-62). These isotopic and geochemical signatures indicate changes in groundwater temperatures and geochemistry are primarily a result of climatic events and recharge points, followed by rock-water interactions. By deduction, the large volume of paleoclimate recharge water undergoes more rock-water interactions in the UZ and SZ, and more mixing of waters from different flow systems due to climatic events than the relatively small volume of water that contacts a seismically produced "zone of alteration." Thus, the large influx of paleoclimate recharge waters, now underneath the repository location and along the transport path, represents the maximum geochemical and temperature variability in the SZ, and overshadows any minor change in groundwater geochemistry due to a transient, seismically-induced event.

In summary, the SZ hydrologic response due to a future seismic event is negligible over the temporal and spatial scale of concern. A seismically-induced hydrologic response in the SZ will not change long-term flow directions or flow paths, and will not have a significant effect on the release of radionuclides to the accessible environment. This FEP is excluded based on low consequence because it will not significantly change radiation exposure to the RMEI or radionuclide releases to the accessible environment.

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.8 Hydrologic Response to Igneous Activity (1.2.10.02.0A)

FEP Description: Igneous activity includes magmatic intrusions which may alter groundwater flow pathways, and thermal effects which may heat up groundwater and rock. Igneous activity may change the groundwater flow directions, water level, water chemistry, and temperature. Eruptive and extrusive phases may change the topography, surface drainage patterns, and surface soil conditions. This may affect infiltration rates and locations.

Screening Decision: Excluded–Low consequence

Screening Argument:

The effects of igneous intrusions on UZ flow and flow paths, topography, surface drainage patterns, surface soil conditions, and infiltration rates are addressed in the UZ FEP analysis report (BSC 2005 [DIRS 174191], Section 6.8.4).

Igneous intrusions within the SZ flow domain are expected to be of low consequence to water table elevations and SZ flow patterns and flow paths for the following reasons. Several analogue sites can be used to estimate the effects of an igneous activity on SZ hydrology. The Paiute Ridge intrusive/extrusive center located in the northeastern margin of the Nevada Test Site is one example. Paleomagnetic, geochronologic, and geochemical data indicate that the complex formed during a brief magmatic pulse representing a single volcanic event (Ratcliff et al. 1994 [DIRS 106634]). The vents and associated dike system formed within a north-northwest-trending extensional graben. The site provides exposures at a variety of depths of the system, including remnants of surface lava flows, volcanic conduits, and dikes and sills intruded into the in situ tuff rock at depths of up to 300 m. Investigation of the site indicates that (1) igneous activities altered rock properties within only a few tens of centimeters out from the rock/dike interface and, at most, a meter perpendicular to an intruding dike; and (2) dike location and orientation was influenced by the orientation of the local stress field and the presence of existing faults (Carter Krogh and Valentine 1996 [DIRS 160928], pp. 7 and 8). Of interest, the SZ permeability observed in the Yucca Mountain region has been interpreted to have a maximum principal permeability direction of approximately north-northeast, which is consistent with the fault and fracture orientation (Ferrill et al. 1999 [DIRS 118941], p. 1). Additional analyses of uncertainty in potential horizontal anisotropy have determined that the most likely direction of maximum principal permeability is approximately north-south (BSC 2004 [DIRS 170010], Section 6.2.6). Coincidentally, the dike margins are parallel and associated with the primary direction of increased or decreased permeability. This parallel to subparallel dike orientation to the principal and maximum permeability orientation, coupled with the limited volume of rock affected by an intruding dike, indicate that magmatic intrusion (dikes) will not significantly affect groundwater flow patterns at the mountain scale, even if the intruding dike differs in permeability.

There are several lines of evidence that support eliminating the effects of an igneous activity on long-term changes in water temperature and geochemistry. Thermal transfer from an intruding dike to the in situ rock can morphologically change the in situ rock to volcanic glass, and provides an indication of affected transfer depths. Analysis of igneous activity at Paiute Ridge (CRWMS M&O 1998 [DIRS 105347], Section 5, p. 57) indicates that thermal transfer into adjacent rock due to an igneous activity is minimal. Igneous activities at the Grants Ridge site produced only localized formation of volcanic glass within the contact zone (CRWMS M&O 1998 [DIRS 105347], Section 5, p. 74 referenced in DTN: MO0310INPDEFEP.000); evidence of any regional hydrothermal response was absent. Additionally, Kuiper (1991 [DIRS 163417], p. 121) suggests if a 10 m km-long, 5 km-deep, and 100 m-wide disc-shaped dike initially intruded into the SZ, the transient rise in the water table due to heat effects would be on the order of 25 m. Studies of natural analogue sites (CRWMS M&O 1998 [DIRS 105347], Section 5, pp. 1 to 2) support the inference that minimal chemical and mineralogical alteration will occur (meters to a few tens of meters) at the interfaces between intruding dikes and the in situ rock due to future igneous activity within the Yucca Mountain region. Lastly, because SZ water chemistry is dominated by the chemical and atmospheric conditions and the large volume of paleoclimate recharge waters, the small volume of igneous-altered rock would have little impact on the characteristics of SZ water chemistry (see FEPs 2.2.08.01.0A–Chemical characteristics of groundwater in the SZ and 2.2.08.03.0A-Geochemical interactions and evolution in the SZ). Thus, the regional SZ geochemistry in the Yucca Mountain vicinity will not be significantly affected by igneous activity. A more detailed discussion of FEPs related to igneous activity is given in *Features, Events and Processes*: *Disruptive Events* (BSC 2005 [DIRS 173981], Section 6.2.2).

In summary, igneous intrusions that are expected to occur in the time frame of 10,000 years after closure will affect a relatively small volume of the SZ and are likely to have the orientation of the intrusive features or be parallel to existing features. Consequently, the intrusion will not have a significant effect on rock permeabilities at the scale that affects site-wide water table elevation, or SZ flow and flow paths. Therefore, the hydrologic response to igneous activity is excluded based on low consequence because it will not significantly change radiation exposure to the RMEI or radionuclide releases to the accessible environment.

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.9 Water Table Decline (1.3.07.01.0A)

FEP Description: Climate change could produce decreased infiltration (e.g., an extended drought), leading to a decline in the water table in the saturated zone, which would affect the release and exposure pathways from the repository.

Screening Decision: Excluded–Low consequence

Screening Argument:

The primary process affecting water table elevation is the cyclical and climatically driven infiltration through the UZ to the SZ (Szabo et al. 1994 [DIRS 100088]). One can predict *relative* future water table elevations based on several physical lines of evidence, such as mineralogy and geochemistry, and fossil, glacial, and marine records. These records indicate a cyclical rise and fall of the water table coincident with the 100,000 to 150,000-year cyclical change in climate punctuated by the periodicity of smaller climate cycles ranging between 10,000 to 40,000 years (Szabo et al. 1994 [DIRS 100088], Figure 6; Forester et al. 1996 [DIRS 100148], p. 52). Reasoned arguments are given below for the maximum depth in which the water table could be lowered within the next 10,000 years, given an unexpectedly dry climate, and the effects of a much lower water table on transport times.

Uncorrected SZ groundwater ages determined from carbon-14 (percent modern carbon) data (DTN: MO0012MAJIONIS.000 [DIRS 153679], Table S00453_001)) and an exponential decay relationship (BSC 2004 [DIRS 170037] equation A6-3) range from about 10,000 to 16,000 years old. Corrections to the groundwater age to account for geochemical interactions are small (BSC 2004 [DIRS 170037] Table A6-7), thus the SZ groundwater composition reflects recharge that occurred up until the late Pleistocene. Groundwater pressures respond much more quickly than groundwater geochemistry to changes in boundary conditions (i.e., recharge rates, inflow from adjacent boundaries). Consequently, water table elevations are more reflective of the current, interglacial, climate pressure pulse.

Present groundwater elevations in Basin and Range Province (which includes the Yucca Mountain region) are reflective of current arid climatic conditions and the time-dependent decrease in infiltration (i.e., lower recharge) of the interglacial climatic interval. The interglacial climatic interval is predicted to persist for 400 to 600 years. After the interglacial-climatic interval, warmer and wetter monsoonal climatic conditions are predicted to persist for approximately 900 to 1400 years. It is predicted that a cooler and wetter glacial-transition climatic condition will follow the brief monsoonal period and will persist for about 8,000 to 8,700 years (BSC 2004 [DIRS 170002], Section 7). However, while not predicted in *Future Climate Analysis* (BSC 2004 [DIRS 170002]), this FEP addresses variability within the interglacial-climatic interval that may produce an extreme arid condition that could potentially cause the current water table to fall significantly. By investigating the geologic, fossil, and mineralogic records, one can ascertain the lower bound in which a water table could potentially fall within the next 600 years, given extremely unusual and increasingly more arid climatic conditions.

An indication of past water table elevations can be found by examining calcite crystal morphology within saturated and unsaturated fractures (Whelan et al. 1998 [DIRS 108865]). Calcite crystals grown below the water table are dense and elongated, having porosities much less than one percent (Szabo et al. 1994 [DIRS 100088]). Calcite crystals grown in unsaturated fractures (above the water table) are distinctly different from those grown in saturated fractures (below the water table). They are less dense, short, and porous (1 to 20 percent porosity); free growing (Szabo et al. 1994 [DIRS 100088]); do not fluoresce or phosphoresce, locally display orange growth banding; and have single-phase fluid inclusions (Whelan et al. 1998 [DIRS 108865]). Whelan et al. (1998 [DIRS 108865]) report evidence of calcite crystal growth, indicative of unsaturated conditions in fracture openings, located 100 to 300 m below the current water table. The evidence suggests the water table dropped to these levels at least once during the last 11.6 million years. Szabo et al. (1994 [DIRS 100088]) studied evidence of past water table fluctuations in Browns Room, a subterranean air-filled room adjacent to the Ash Meadows discharge area. Their investigations indicate the water table dropped by at least 6 m from its current level between 92,000 and 53,000 years ago. (Szabo et al. 1994 [DIRS 100088] do not give estimates of how much beyond 6 m the water table may have declined.) Based on the above findings one can conclude there is a relatively low probability that the water table will drop by 300 m. However, if the water table were to fall by as much as 300 m, the change in flow path and transport time that a plume would take from the repository to the 18-km compliance boundary would be of low consequence. The rationale for this statement follows.

Based on the SZ base-case flow calculations, the transport pathways, under current and wetter climatic conditions, are confined to the following hydrostratigraphic units: the Crater Flat-Prow Pass, Crater Flat-Bullfrog, and Crater Flat-Tram (subunits of the Lower Volcanic Aquifer), the Upper Volcanic Confining Unit, the Upper Volcanic Aquifer, the Undifferentiated Valley Fill, and the Alluvium. Of these seven units, most transport pathways pass through the Crater Flat-Bullfrog hydrostratigraphic unit (BSC 2004 [DIRS 170037], Section 6.6.2.3). The collective thicknesses of these units along the potential transport path are well over 300 m (BSC 2004 [DIRS 170037], Figures 6-43). The Prow Pass and Bullfrog units are the most permeable volcanic units in the flow and transport path (BSC 2004 [DIRS 170037], Table 6-19). Lowering the water table by as much as 300 m in the volcanic units would put the potential transport path primarily in the Tram subunit and potentially in the Lower Volcanic Confining unit. The permeability of these units is several orders of magnitude lower than the Bullfrog. Therefore, if the water table were lowered by as much as 300 m, transport times would be greater than transport through all the Crater Flat subunits.

Given the collective alluvium and valley-fill thickness of 400 to 700 m, and the uncertainty in transport properties through both the undifferentiated valley fill and alluvium units, a potential lowering of the water table from its current elevation would not reduce predicted transport times. The uncertainty as to whether a plume would flow in the alluvium and valley fill or the volcanic units, due to a lower water table, is implicitly captured using stochastic simulations of the location of the northern and western boundaries of the alluvial units in *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012], Section 6.5.2.2).

Additionally, a lowering of the water table would create longer transport pathways through the UZ, thus delaying and potentially reducing the total mass of radionuclides reaching the SZ, and creating lower hydraulic gradients. Lower gradients in the SZ equate to slower groundwater SZ specific discharge rates, which mean longer SZ transport times to the compliance boundary.

Lastly, paleoclimate records indicate arid climatic conditions are short, relative to wetter conditions (Forester et al. 1996 [DIRS 100148], p. 52). Investigations of proxy climate records indicate climatic conditions during the past two million years were much wetter than current climatic conditions for about 70 to 80 percent of the time (Szabo et al. 1994 [DIRS 100088], Figure 6). Analysis of Searles Lake deposits indicate extreme arid conditions have only occurred twice during the past 600,000 years, once around 290,000 years ago and the other within the last 10,000 years. One can infer the current water table is now at a low point in the 150,000 to 300,000 years climate cycle and will not significantly drop below current groundwater elevations during 10,000 years after closure. Based on the above evidence, if the water table were to decline, the likelihood of it declining 140 to 300 m below its current level is very low.

Given the above rationale, it is not likely the water table will decline to levels lower than 140 to 300 m from its present position. However, if the water table were to decline to these levels, the overall effect would be to increase SZ transport times and, thus, not adversely affect repository performance. Therefore, water table decline is excluded based on low consequence because it has no adverse effects on performance.

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.10 Water Table Rise Affects SZ (1.3.07.02.0A)

FEP Description: Climate change could produce increased infiltration, leading to a rise in the regional water table, possibly affecting radionuclide release from the repository by altering flow and transport pathways in the SZ. A regionally higher water table and change in SZ flow patterns might move discharge points closer to the repository.

Screening Decision: Included

Screening Argument: N/A

TSPA Disposition:

The TSPA-LA implicitly models a higher water table in the SZ to reflect wetter climatic conditions (resulting in an increase in time-dependent infiltration) with the use of flux multipliers. The rationale for the use of flux multipliers is based, in part, on the impact a wetter climate would have on the current water table elevations measured in wells within the SZ flow domain. These water-level measurements are used to derive a potentiometric surface representative of current climate conditions within the Yucca Mountain vicinity, as reported in

Water-Level Data Analysis for the Saturated Zone Site-Scale Flow and Transport Model (BSC 2004 [DIRS 170009], Section 6.4).

Flux multipliers are incorporated in the convolution integral method (BSC 2005 [DIRS 174012], Section 6.5). Flux multipliers scale the base-case SZ radionuclide BTCs, effectively modeling the impacts a higher water table would have on transport times to the 18-km boundary (BSC 2005 [DIRS 174012], Section 5). Three flux multipliers are used to characterize changes in water table elevations reflective of three climatic conditions. Current climatic conditions are represented by a flux multiplier of 1.0; for a monsoonal climate the multiplier is 2.7; and for a glacial-transition climate the multiplier is 3.9 (BSC 2005 [DIRS 174012], Table 6-5). An upper bound estimate of SZ transport times to the 18-km boundary, reflective of a higher water table produced during a glacial-transition climatic condition, is conservatively bounded with the use of the 3.9 flux multiplier. The rationale supporting this assumption is given below.

SZ transport times at the 18-km boundary using the 3.9 flux multiplier method (representative of a glacial-transition climate) have been compared to transport times performed on an alternative model domain to corroborate the base-case model. The alternative model domain method allows the water table to be 100 m higher than present conditions under the repository footprint (Section 6.4.5.2.1 of *Saturated Zone Site-Scale Flow Model,* (BSC 2004 [DIRS 170037]), which is approximately equal to the upper estimate that the water table would rise under the repository given a future glacial-transition climatic condition. Conservative and sorbing radionuclide BTCs show initial tracer breakthrough times (the leading edge of the BTC) are at least an order of magnitude greater for the alternative model method compared to breakthrough using the flux multiplier method. Additionally, BTC trailing-edge times for the alternative model domain are well over an order of magnitude greater compared to those derived using a flux multiplier (BSC 2004 [DIRS 170036], Appendix E, and Figures E-1 and E-2). The longer transport times using the alternative model are a function of several factors. The higher water table incorporated in the alternative model domain enables both types of tracers to pass through less permeable upper volcanic confining units, resulting in considerably longer path lengths and transport times. For these simulations, longer transport times are due to a combination of several factors. A higher water table partitions flow through volcanic units having less effective (fracture) permeability, thus, facilitating greater matrix diffusion. Additionally, a higher water table promotes longer flow paths through the porous alluvium, equating to longer alluvium transport times.

Based on the results from this alternative model, which explicitly simulates a higher water table, it is assumed the simplified, flux multiplier method results in more rapid radionuclide transport to the 18-km boundary than the explicit model. That is, the flux multiplier method does not underestimate groundwater transport times given wetter climate conditions. This simplified representation of the effect of climate change on water table elevations conservatively estimates the effects of a higher water table on SZ transport times to the 18-km boundary.

Water table rise associated with future climates is explicitly included in the radionuclide transport simulations for the UZ. To include this water table rise in the TSPA-LA calculations, the water table elevation is instantaneously increased by 120 m in the UZ model domain when the climate changes from present-day to monsoon climate. The same water table elevation is also used for the glacial-transition climate. This is a conservative approach that uses the reasonable upper bound (120 m rise) from several estimates of the water table elevation under the repository in the past (BSC 2004 [DIRS 170037], Section 6.4.5).

Supporting Reports:

- *Water-Level Data Analysis for the Saturated Zone Site-Scale Flow and Transport Model (BSC 2004* [DIRS 170009])
- *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037]
- *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036])
- *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]).

6.2.11 Water Management Activities (1.4.07.01.0A)

FEP Description: Water management is accomplished through a combination of dams, reservoirs, canals, pipelines, and collection and storage facilities. Water management activities could have a major influence on the behavior and transport of contaminants in the biosphere.

Screening Decision: Included

Screening Argument: N/A

TSPA Disposition:

For the SZ, this FEP pertains to the impacts on projected SZ flow and transport times due to the construction of future water management edifices. The effects of existing water management activities on the saturated flow system, while not directly quantifiable, are implicitly incorporated in the current potentiometric surface developed from current water-level measurement taken within the Yucca Mountain vicinity and reported in *Water-Level Data Analysis for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2004 [DIRS 170009], Section 6.4). Future water management activities, are presumed to be those currently in practice as given by regulation 10 CFR Section 63.305(b) [DIRS 173273], which states:

> DOE should not project changes in society, the biosphere (other than climate), human biology, or increases or decreases of human knowledge or technology. In all analyses done to demonstrate compliance with this part, DOE must assume that all of those factors remain constant as they are at the time of submission of the license application.

The *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]) assumes the SZ flow domain is a steady state system (BSC 2005 [DIRS 174012], Section 6.3), thus, implicitly adopting the impact of future water management activities on the predicted flow and transport paths. Water management activities are explicitly included in the biosphere models that determine irrigation intensity, and fraction of overhead irrigation, through the biosphere's “fish” and “plant” mathematical submodels that ascertain the potential dose to RMEI. This FEP, and its impact on the RMEI, is discussed in the *Evaluation of Features, Events and Processes (FEPs) for the Biosphere Model* (BSC 2005 [DIRS 174107], Section 6.2.10).

Supporting Reports:

- *Water-Level Data Analysis for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2004 [DIRS 170009])
- *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]).

6.2.12 Wells (1.4.07.02.0A)

FEP Description: One or more wells drilled for human use (e.g., drinking water, bathing) or agricultural use (e.g., irrigation, animal watering) may intersect the contaminant plume.

Screening Decision: Included

Screening Argument: N/A

TSPA Disposition:

The effects of wells on the dose to the RMEI are included by assuming all of the radionuclide mass that reaches the 18-km accessible environment is contained in the representative volume of groundwater from which the RMEI obtains water (BSC 2005 [DIRS 174012], Sections 5 (3) and 6.3.3). For the individual and groundwater protection standard concentrations, it is assumed that all radionuclide mass that crosses the 18-km boundary is dissolved in the 3,000 acre-ft of water per year (in accordance with 10 CFR Part 63 Subparts 63.312(c) and 63.332(a)(3) [DIRS 173273]). The location of future wells and their impact on the potentiometric surface is based on consideration of present well locations within the SZ flow domain as reported in *Water-Level Data Analysis for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2004 [DIRS 170009], Section 6.4). Hydraulic heads in these existing wells are used in the calibration process in the site-scale SZ base-case flow model (BSC 2004 [DIRS 170037], Section 6.6.1.3).

Supporting Reports:

- *Water Level Data Analysis for the Saturated Zone Site Scale Flow and Transport Model* (BSC 2004 [DIRS 170009]).
- *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037]) (While FEP 1.4.07.02.0A is not explicitly identified in this report (BSC 2004 [DIRS 170037], Table 6-1), the FEP is addressed in the report).
- *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]).

6.2.13 Transport of Particles Larger than Colloids in the SZ (2.1.09.21.0B)

FEP Description: Particles of radionuclide-bearing material larger than colloids could be entrained in suspension and then be transported in water flowing through the SZ.

Screening Decision: Excluded–Low consequence

Screening Argument:

This FEP deals with particles larger than 1 μm, the upper limit in colloidal size particles that could potentially transport radionuclide-bearing material. Because radionuclide bearing particles larger than 1 μm (BSC 2005 [DIRS 174290], Section 1.2) are not considered to move from the waste packages through the engineered barrier system (EBS) and UZ (BSC 2005 [DIRS 174191], Section 6.4.4), these large particles would first have to be formed in the SZ, then transported downstream to the compliance boundary. Two processes, precipitation and colloid accretion and flocculation, could contribute to the formation of large radionuclide bearing particles. Once formed, these larger particles could be entrained (i.e., rinsed) in the groundwater downstream for some distance before filtering or settling.

Horizontal flow is the dominant flow component along the potential SZ transport path. Large particles will be carried, horizontally, along contorted flow paths, encountering varying fracture widths, fracture asperities (degree of roughness) and orientations, and less mobile regions. A large particle will move along this flow path, losing energy due to frictional forces to the point where its velocity will be reduced such that it will settle out or be filtered. It is only possible for the smallest of large particles (i.e., slightly larger than a colloid) to be sustained along the entire 18-km flow path if the upward vertical component of the pore water velocity exceeds the particle's settling velocity. Diffusive movement of the particles in the SZ is of low significance. Due to a large size, the particle diffusion will be very limited. Gravitational settling was compared to the diffusive movement in (BSC 2005 [DIRS 174191], Section 6.4.4) and it was concluded that gravitational settling would dominate.

An estimation of one micron particle's settling velocity (*sv*) is derived using Stokes' Law (Hillel, 1980 [DIRS 101134], Chapter 4, F):

$$sv = \frac{gL^2(D_p - D_w)}{18V} \qquad \text{(Eq. 6-4)}$$

with the following inputs:

- Particle diameter (L) of 1 micron (1×10^{-6} m).
- Particle density (D_p) of 2,500 kg/m^3 (BSC 2005 [DIRS 174290], Appendix I, Section I.1).
- Water density (D_w) of 1,000 kg/m^3 at 20ºC (Streeter and Wylie 1979 [DIRS 145287], p. 534).

- Water dynamic viscosity (V) of 1.005×10^{-3} Ns/m^2 at 20ºC (Viswanath and Natarajan 1989 [DIRS 129867], p. 715).

- Acceleration of gravity (g) is 9.81 m/s^2.

Using the above inputs (appropriate for 20°C), the settling velocity order of magnitude is 8×10^{-7} m/s (0.07 m/d). Thus, to keep the smallest of "large" particles sustained along the entire path length, the upward vertical component of the pore-water velocity must exceed the settling velocity of 8×10^{-7} m/s. This is unlikely for several reasons.

1. Minor increases in temperature cause a large increase in settling velocity, enabling relatively small particles to settle more readily. The temperature range for Yucca Mountain SZ waters is approximately 20°C to 55°C, with the majority of temperatures within the upper 20°C to lower 30°C (DTN: MO0102DQRBTEMP.001 [DIRS 154733]). The temperature dependent density and viscosity of water for this temperature range will result in a higher settling velocity. Viscosity varies most with temperature. Consequently, the variability in settling velocity would most dramatically be increased due to the large variability in viscosity.

2. The assumed diameter for colloids adopted in this argument (1 µm) is upper bounding. Therefore, any particles "larger" than this upper bound diameter will have a larger settling velocity than that determined using Equation 6-4, and will more readily settle out of solution.

3. Using Stokes' Law to calculate sustainability of particles in an "open" solution presumes particle settling is unhindered as it moves horizontally, which is not the case in porous media. SZ flow is not along open and unhindered flow paths. In the volcanic hydrostratigraphic units, SZ flow primarily passes through the Crater Flat-Bullfrog, Crater Flat-Tram, Crater Flat-Prow Pass, the Upper Volcanic Aquifer, and the Upper Volcanic Confining Unit. Of these five volcanic units, the majority of SZ flow passes through the Crater Flat-Bullfrog hydrostratigraphic unit (BSC 2004 [DIRS 170037], Table 6-36). In the Crater Flat group, the SZ flow passes through fractured zones consisting of rubblized and brecciated material producing large variability in permeability. On a regional scale, fracture permeability in the Crater Flat-Bullfrog, Crater Flat-Tram, and Crater Flat-Prow Pass hydrostratigraphic units ranges over three orders of magnitude (BSC 2004 [DIRS 170037], Section 6.6.1.4). Locally, this variability is even greater. This leads to variability in the magnitude of the vertical component of pore/fracture water velocity. Thus, a large particle, if suspended when transported downstream, will encounter low permeability and rubblized zones where the vertical flow vector is less than the settling velocity. In these locations, large particles will settle out.

4. A calculation of the upward vertical flow component in two known SZ locations shows the settling velocity is not exceeded. Utilizing the relationships between the hydraulic conductivity, permeability and Darcy's law to compute specific discharge and pore velocity (Domenico and Schwartz [DIRS 100569], equations 3.23, 10.2 and 16.2) as follows:

a. The difference between the carbonate aquifer head measurements (752.4 m at UE-25p#1) and shallower measurements in the same area (730.2 m at UE-25c#1, UE-25c#2, UE-25c#3) is about 20 m (BSC 2004 [DIRS 170037], Table 6-18). The elevation of the two measuring points are -410 m for UE-25p#1 and about 500 m average for c#1, c#2, c#3. This gives an average vertical gradient of 20 m/910 m or 0.022. The confining unit between the carbonate aquifer and the Bullfrog unit (a primary flow path) has a mean permeability value of 2.0×10^{-15} m^2 (BSC 2004 [DIRS 170037], Table 6-19). Converting permeability to hydraulic conductivity (at 40ºC) gives about 3×10^{-6} m/s. This calculation assumes a groundwater temperature at a depth corresponding to 40°C. Multiplying by the vertical gradient gives about 2×10^{-10} m/s for the specific discharge. If the effective porosity for the upper carbonate aquifer is 0.01 (BSC 2005 [DIRS 174012], Section 6.5.2.20.), the calculated upward velocity is 6.5×10^{-8} m/s, which is less than calculated settling velocity.

b. The difference between the alluvium head measurement at NC-EWDP 19D and NC-EWDP 19P is 5.3 m (DTN GS010908312332.003 [DIRS 168699]); the elevation difference between the bottom of the monitored intervals in these two wells is 293 m, yielding a vertical gradient of 0.018 (5.3 m/293 m). However, the levels for NC-EWDP-19D represent a composite water level for both alluvium and the underlying volcanics, so this gradient may represent a gradient between the volcanics and the alluvium (BSC 2004 [DIRS 170009], Section 6.3.2). The combined permeability value for the alluvium is 2.7×10^{-13} m^2 (BSC 2004 [DIRS 170037], Table 7-4), which converted to hydraulic conductivity (at 40°C) gives 4.0×10^{-6}m/s. This calculation assumes a groundwater temperature at a depth corresponding to 40°C. Multiplying this by the vertical gradient gives a specific discharge of 4.8×10^{-8} m/s. For the alluvium, the mean effective porosity is 0.18 (BSC 2005 [DIRS 174012], Table 6-8); dividing specific discharge by mean effective porosity gives the upward vertical velocity of about 4.0×10^{-7} m/s, which is less than the calculated settling velocity.

5. Laboratory and field measurements on Yucca Mountain tuffs indicate that colloid filtering and settling is a mechanism that removes colloid size particles from solution (BSC 2004 [DIRS 170006], Sections 6.4.2 and 7.1). Laboratory experiments performed on 30-cm length core tubes demonstrated that colloids “stick” and settle along fracture surfaces, especially in those fractures oriented horizontally and parallel to the flow direction. Results from these laboratory experiments are supported with field observations. At the Nevada Test Site, a five-order decrease in plutonium colloid concentrations was observed in ER-20-5 wells for colloids formed as a result of the Benham underground nuclear tests. The ER-20-5 wells are located several kilometers downstream from the test area (BSC 2004 [DIRS 170006]). Physical filtering was the process attributed to the loss of colloid mass downstream. Because filtering occurs for colloidal size particles, this process will be exacerbated for larger particles.

Transport of particles larger than colloids is screened out on the basis of low consequence because (1) no radionuclide bearing particles larger than colloids are introduced into the SZ from the UZ (BSC 2005 [DIRS 174191], Section 6.4.4); (2) large particles will not be suspended for great distances along the flow paths, given the variable vertical velocity component that would be encountered along the transport path; and (3) the highly variable size, shape, orientation, and roughness of the fracture voids along the transport pathway promote both settling and filtering. Transport of particles larger than colloids is excluded based on low consequence because it will not significantly change radiation exposure to the RMEI or radionuclide releases to the accessible environment.

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.14 Stratigraphy (2.2.03.01.0A)

FEP Description: Stratigraphic information is necessary information for the performance assessment. This information should include identification of the relevant rock units, soils and alluvium, and their thickness, lateral extents, and relationships to each other. Major discontinuities should be identified.

Screening Decision: Included

Screening Argument: N/A

TSPA Disposition:

The stratigraphic (i.e., hydrologic) nature of the rock as it affects flow and transport is incorporated into the TSPA-LA site-scale flow and transport models (BSC 2004 [DIRS 170037] and BSC 2004 [DIRS 170036]). The primary hydrogeologic subdivisions are based on and coincide with (1) common permeability and porosity characteristics (on a regional scale) of the rock and (2) whether the rock's primary mode of origin is volcanic, clastic, sedimentary (carbonates), or alluvial in nature (BSC 2004 [DIRS 170037], Section 6.3.2.9). The hydrogeologic subdivisions employed for the TSPA-LA are a synthesis of the hydrogeologic framework model (BSC 2005 [DIRS 174109]) and the calibrated *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037], Section 1).

In all, there are 19 hydrogeologic units employed in the formulation of the base-case SZ flow model (BSC 2004 [DIRS 170037], Section 6.5.3.3), and the SZ flow and transport abstraction (BSC 2005 [DIRS 174012], Section 6.5.2). These same units are modeled in the base-case SZ transport model (BSC 2004 [DIRS 170036]), as a result of the transport model being constructed from the SZ base-case flow model. The uncertainty in transport parameters specific to stratigraphy, such as effective diffusion, matrix porosity, and bulk density are described in *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012], Sections 6.5.2.6, 6.5.2.18, and 6.5.2.19).

The 19 hydrogeologic units can be grouped into five basic SZ hydrogeologic subdivisions: the upper volcanic aquifer, upper volcanic confining unit, lower volcanic aquifer, lower volcanic confining unit, and lower carbonate aquifer (BSC 2004 [DIRS 170037], Section 6.3.2.9). In the

SZ base-case flow model (BSC 2004 [DIRS 170037], Section 6.5.3.4), major discontinuities between the 19 hydrostratigraphic units are implemented by including 17 discrete features. These features reflect the degree of fracturing, faulting, fault orientation, and mineralogical alteration of glassy materials to zeolites and clay minerals. In the hydrogeologic units where flow and transport are expected to take place, the alluvium units, Crater Flat Group, and the upper volcanic confining units (BSC 2004 [DIRS 170037], Section 6.6.2.3), variability in transport properties between the major hydrogeologic units is implemented using a range of sampled parameters assigned to each unit for a particular realization (BSC 2005 [DIRS 174012], Section 6.5.2). The uncertainty in the contact between volcanic rocks and alluvium at the water table are determined for a particular realization by the parameters FPLAW and FPLAN (BSC 2005 [DIRS 174012], Section 6.5.2.2). These parameters are used to independently and uniformly vary the northern and western contacts of the volcanic rocks and alluvium at the water table. For the fractured volcanic units, uncertainty in the spacing between intervals conducting significant quantities of groundwater is assessed in *Probability Distribution for Flowing Interval Spacing* (BSC 2004 [DIRS 170014]). Hydraulic and tracer testing in the fractured volcanic hydrostratigraphic units has been conducted in the area downgradient of the repository (BSC 2004 [DIRS 170010]). How the physical properties of stratigraphic units are modeled is discussed in FEP 2.2.03.02.0A–Rock properties of host rock and other units. Further discussions of the various aspects of stratigraphy affecting flow and transport in the SZ are found in *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012], Sections 6.5.2, 6.5.2.1, 6.5.2.2, 6.5.2.3, 6.5.2.6, 6.5.2.18 and 6.5.2.19) and *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036], Section 6.3).

Supporting Reports:

- *Hydrogeologic Framework Model for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2005 [DIRS 174109])
- *Probability Distribution for Flowing Interval Spacing* (BSC 2004 [DIRS 170014])
- *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037])
- *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036])
- *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012])
- *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010]).

6.2.15 Rock Properties of Host Rock and Other Units (2.2.03.02.0A)

FEP Description: Physical properties such as porosity and permeability of the relevant rock units, soils, and alluvium are necessary for the performance assessment. Possible heterogeneities in these properties should be considered. Questions concerning events and processes that may cause these physical properties to change over time are considered in other FEPs.

Screening Decision: Included

Screening Argument: N/A

TSPA Disposition:

Geologic features and heterogeneous hydrostratigraphic units are explicitly included in the SZ Transport Abstraction Model (BSC 2005 [DIRS 174012]) as cells with specific hydrologic parameter values in a configuration based on the hydrogeologic framework used in the *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037], Section 6.3.2). Available geologic information of rock properties that affect SZ flow and transport in the Yucca Mountain region is used to determine the 19 hydrostratigraphic units modeled in the site-scale SZ flow domain (BSC 2005 [DIRS 174109]).

There are numerous broad and distinct zones in the SZ flow model categorized as "features," which are directly or indirectly affected by faults, zones of mineralogical alteration along faults, or contact zones between units (BSC 2004 [DIRS 170037], Section 6.5.3.4, Table 6-17). The zones are categorized depending upon how their unique rock property characteristics, most notably porosity and permeability, affect flow and transport. The nature of the rock properties in these zones are modeled to act as either barriers or conduits to SZ flow (BSC 2004 [DIRS 170037], Section 6.5.3.4, Table 6-17). They are grouped as follows: (1) zones of permeability enhancement parallel to faults and zones of permeability reduction perpendicular to faults, (2) fault zones with enhanced permeability, (3) contact zones between units and nonfault zones, (4) faults and zones representing regions of lower permeability caused by hydrothermal alteration, and (5) zones of unknown features. Details of the 17-modeled features are given in the FEP 2.2.07.13.0A-Water-conducting features in the SZ.

In the *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037], Section 6.6.1.4), a base-case permeability flow field is generated. Variability in permeability, due to the presence of faults and fractures, is accounted for in the base-case flow model by incorporating 17 key heterogeneous features within the 19 modeled hydrostratigraphic units (BSC 2004 [DIRS 170037], Sections 6.3.1 and 6.3.2.2).

The presence of faults and fractures can either increase or decrease permeability within a unit. The SZ transport abstraction model and the SZ one-dimensional transport model (both models described in *Saturated Zone Flow and Transport Model Abstraction*, BSC 2005 [DIRS 174012], Section 6.5 and Table 6-2) take the base-case transport model and incorporate additional uncertainty, heterogeneities, and potential changes in permeability through the stochastically sampled GWSPD (BSC 2005 [DIRS 174012], Section 6.5.2.1). This results in multiple heterogeneous permeability fields. Additional uncertainty and spatial variability in rock properties in the SZ transport abstraction model are encompassed within uncertainty distributions for the following stochastically sampled parameters: (1) HAVO, (2) effective porosity in the alluvium units 7 and 19 (NVF7 and NVF19), (3) FISVO, (4) FPVO, (5) alluvium bulk density (bulk density), (6) sorption coefficients (K_d) for the nine classes of radionuclides modeled in both the alluvium and volcanic units, and (7) LDISP. The above parameters are described in Sections, 6.5.2.3, 6.5.2.4, 6.5.2.7, 6.5.2.8, 6.5.2.9, and 6.5.2.10 of the SZ flow and transport model abstraction (BSC 2005 [DIRS 174012]). Uncertainty in the flowing interval spacing parameter is assessed in *Probability Distribution for Flowing Interval Spacing* (BSC 2004 [DIRS 170014]). The basis for anisotropy in permeability in the volcanic units and assessment of groundwater specific discharge in the alluvium are discussed in *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010]). Other parameters that effectively model the uncertainty in rock parameters are the contact zone between the alluvium and the volcanic units and volcanic and alluvium porosities, bulk densities, which are discussed in Sections 6.5.2.2, 6.5.2.14, 6.5.2.15, 6.5.2.16, 6.5.2.17, 6.5.2.18, 6.5.2.19, and 6.5.2.20 of the SZ flow and transport model abstraction (BSC 2005 [DIRS 174012]). The impacts of rock properties on sorption coefficients uncertainty are discussed in the *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036], Sections 6.3 and 6.4 and Appendix A).

The uncertainty in rock properties to be modeled along the alluvium-volcanic contact boundary is explicitly accounted for through the probabilistically sampled parameters, FPLAW and FPLAN (BSC 2005 [DIRS 174012], Section 6.5.2.2), which define the western and northern boundaries, respectively, of the alluvium (valley-fill aquifer). These parameters determine whether alluvial or volcanic rock properties will be modeled within an area along the alluvial-volcanic interface.

Supporting Reports:

- *Hydrogeologic Framework Model for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2005 [DIRS 174109])
- *Probability Distribution for Flowing Interval Spacing* (BSC 2004 [DIRS 170014])
- *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037])
- *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036])
- *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012])
- *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010]).

6.2.16 Seismic Activity Changes Porosity and Permeability of Rock (2.2.06.01.0A)

FEP Description: Seismic activity (fault displacement or vibratory ground motion) has a potential to change rock stresses and result in strains that affect flow properties in rock outside the excavation-disturbed zone. It could result in strains that alter the permeability in the rock matrix. These effects may decrease the transport times for potentially released radionuclides.

Screening Decision: Excluded–Low consequence

Screening Argument:

Plate tectonic activity has imparted crustal extension stresses within the Basin and Range Province (which includes the Yucca Mountain region) during the past 12 million years. The height of this activity occurred between 10 and 12 Ma, with estimated extension rates ranging between 10 and 30 mm/year (National Research Council 1992 [DIRS 105162], Chapter 2). During this period, major faults and fractures within the Yucca Mountain vicinity were created. Approximately 5 Ma, regional extension stresses declined to 5 to 10 mm/year; currently, extension rates are still in a declining state (National Research Council 1992 [DIRS 105162], Chapter 2). On a local scale, regional extension rates impart local extension, compression, and shear stresses on the crust, depending on location, depth, and juxtaposition to parent rock units and existing faults. Release of stress results in seismic activities that create vibratory motion, faults (rupture), fault displacement, or areal redistribution of stresses not associated with specific faults. Vibratory stresses caused by seismic activity can alter the hydrologic properties of the parent rock. A seismic event can permanently affect rock hydrologic properties by (1) causing a change in pore pressure, which is usually a product of regional stress changes; or (2) an increase or decrease in permeability produced by either dilation, compression, or breakage of granular structures produced from dynamic ground motion.

A seismic event in the Yucca Mountain region is most likely to cause movement along existing faults and fractures, rather than developing new faults (BSC 2005 [DIRS 173981], Section 6.2.1.10). It also may change rock and intergranular stresses, affecting rock hydrologic properties due to the creation of brecciation and gouge zones adjacent to the faults and existing fractures, and may possibly create new fractures (outside of the brecciated zone). This disturbed rock zone, labeled herein as a "zone of alteration," is correlated with the amount of fault offset (Sweetkind et al. 1997 [DIRS 100183]). Faults with 1 m to 5 m of cumulative offset have a zone of increased fracturing of only 1 m to 2 m; faults with tens of meters of offset can have a zone of fracturing up to tens of meters wide (Sweetkind et al. 1997 [DIRS 100183], pp. 66 to 71). Existing rock hydrologic properties in the zone of alteration reflect the cumulative response of a dynamic seismic past, demonstrative of rapid extension rates in existence 10 to 12 Ma, and, to a lesser extent, the lower extension rates in effect today.

Expert elicitation, documented in the Probabilistic Seismic Hazard Analysis (PSHA) report (CRWMS M&O 1998 [DIRS 103731], Sections 4 and 8), provides information that can be used to assess the effects of a seismic event on the hydrologic properties of faults and the host rock. As part of the PSHA, six teams of experts evaluated the available data to assess the fault displacement potential for 9 sites that represent the range of fault conditions in the Yucca

Mountain vicinity (CRWMS M&O 1998 [DIRS 103731], Figure 4-9). The teams also characterized the uncertainty in their assessment by defining alternative models and approaches and assigning them weights. For each combination of alternatives, results for each site were provided as the annual frequency with which given levels of fault displacement would be exceeded. Uncertainty in the results was characterized by calculating the mean hazard and various percentile values. Results for each team were then combined using equal weights to determine the integrated fault displacement hazard (CRWMS M&O 1998 [DIRS 103731], Sections 4 and 8).

One region of interest in the SZ flow domain is the area between Solitario Canyon and the Ghost Dance faults, identified as Site 8 by the PSHA group (CRWMS M&O 1998 [DIRS 103731], Site 8 in Figure 4-9), which is the source area for most of the SZ flow paths. In this region, the PSHA group assessed the mean displacement for intact host rock in the vicinity of the repository to be less than 0.1 cm for a 1×10^{-8} annual-exceedance probability (CRWMS M&O 1998 [DIRS 103731], Section 8.2.1). This area encompasses the same rock type as that along the origin of the SZ flow and transport paths. Therefore, it is inferred that future seismic activity will not result in any significant new faults and fractures in the intact host rock, nor will it alter the hydrologic properties in the existing 'zone of alteration' within that region that would affect SZ flow path origins. Flow path trajectories or flow velocities will not be significantly altered given predicted seismic activity within the area bounded by the Solitario Canyon and Ghost Dance faults for 10,000 years after closure.

Excluding the Solitario Canyon and Bow Ridge faults, the range of the expert teams' results for intrablock fault displacement, taking into account alternative approaches, is approximately 0.1 – 4.5 m at an annual exceedance probability of 1×10^{-8} (CRWMS M&O 1998 [DIRS 103731], Figures 8-17 to 8-27). This is taken as an upper limit for faults within the Yucca Mountain region. Incorporating the weights for each team's alternative approaches and combining the results for all six teams using equal weight, the mean displacement hazard varies from less than 0.1 m to approximately 2.5 m (CRWMS M&O 1998 [DIRS 103731], Figures 8-4 to 8-12).

The exceptions to this displacement range are the predicted displacements for the Solitario Canyon and Bow Ridge faults (CRWMS M&O 1998 [DIRS 103731], Sites 2 and 1 in Figure 4-9), which are block-bounding faults and are expected to have higher displacements. Extrapolating the PSHA results out to the annual exceedance probability of 1×10^{-8} results in a 13 m approximate mean displacement for the Solitario Canyon fault and a 6 m approximate mean displacement for the Bow Ridge fault (CRWMS M&O 1998 [DIRS 103731], Figure 8-2 and 8-3). These displacements will not affect SZ transport and flow paths for the following reasons:

- The Solitario Canyon fault has a cumulative displacement of approximately 260 m where it intersects the Enhanced Characterization of the Repository Block (ECRB) Cross-Drift. With this relatively large displacement, its zone of alteration consists of approximately a 20 m brecciated and gouge zone (Mongano et al. 1999 [DIRS 149850], pp. 59-65). The 13 m predicted displacement represents a fraction of the fault's response to multiple seismic events imposed in the region for many millennia. It is inferred, given estimated future fault displacements inclusive of the approximately 13 m displacement for the Solitario Canyon fault, the hydrologic properties in the zone of alteration will not be significantly altered from current conditions in the next 10,000 years. Detailed discussions on the effects of seismic events on rock properties are provided in *Features, Events, and Processes: Disruptive Events* (BSC 2005 [DIRS 173981], Sections 6.2.1.8 to 6.2.1.11).

- The Bow Ridge fault is one of many faults included in the areally extensive faulted region identified as the "Imbricate Fault Zone" in the *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037], Table 6-17, and Figure 6-37). The Imbricate Fault Zone is modeled in a parallelogram-shaped region encompassing an area approximately 3.5 km wide and 8 km long. It includes highly fractured and brecciated zones and numerous interconnected faults, the Bow Ridge fault being one. Due to the higher incidence of interconnected fractures and faults located in this area, the SZ flow and transport model specifically incorporates lower anisotropy ratios and relatively higher permeabilities here than other volcanic regions in the SZ flow domain (BSC 2004 [DIRS 170037], Table 6-17, and Figures 6-37 and Figure 6-7). Because the Imbricate Fault Zone is areally extensive and includes numerous faults and their attendant zones of alteration, a 6 m fault displacement the Bow Ridge fault would not alter the range of effective permeabilities attributed to this region. All other displacement hazard points identified by the PSHA group are outside of the predicted SZ flow paths and, thus, will not affect SZ flow paths.

- An investigation conducted by the National Research Council (1992 [DIRS 105162], Chapter 5) looked at water table fluctuations, given a predicted seismic event. Results from this report support the assumption that a future seismic event will not permanently alter the regional hydrologic properties of intact host rock. The group looked at two modeling approaches in estimating the change in water table elevations given a seismically induced event: (1) a dislocation approach, where zones of extension on one side of a fault are balanced by compression across the fault; and (2) the more realistic "changes in regional stress" approach caused by normal fault slippage in regions of extension. The regional stress approach evaluates the effect of stress on pore pressure, which is dependent on the elastic properties of the bulk rock and the mineral grains. The extent of water table fluctuations differed for both models. By adopting the dislocation model, the water table rose approximately 10 m. Adopting the regional stress approach resulted in maximum water table rise of 50 m. The latter approach assumes realistically conservative rock and mineral elastic properties. The panel concluded, regardless of what approach is taken, the maximum water table rise, given a seismic event, would be less than 50 m and transient in nature. Because water table fluctuations were transient for both modeling approaches, it is inferred that a future seismic event (predicted over the next 10,000 years) will not permanently alter the rock hydrologic properties (including pore pressures) on a regional scale.

Observations of water table responses to recorded seismic events support the above modeling results. O'Brien (1993 [DIRS 101276]) analyzed water level fluctuations at Yucca Mountain due to earthquakes. Fluctuations range from 90 cm related to a 7.5 magnitude earthquake near Landers, California (approximately 420 km from Yucca Mountain) to 20 cm for a second quake of 6.6 magnitude near Big Bear Lake, California (approximately 400 km from Yucca Mountain). More notably, a 5.6 magnitude quake at Little Skull Mountain (approximately 23 km from Yucca

Mountain) resulted in a maximum fluctuation of 40 cm at one well, with water levels in another well declining approximately 50 cm over the three days following the earthquake. Water levels in that well returned to prequake levels over a period of about six months. Implicit in the observations, given the short duration and relatively small magnitude of seismically induced water table fluctuations, was that a seismically induced permanent change in regional rock hydrologic properties from the observed earthquakes did not occur.

As stated earlier, existing rock hydrologic properties along a fault's zone of alteration reflect the cumulative response to cumulative displacements of a dynamic seismic past. Because the Yucca Mountain region is now experiencing lower extension rates and is tectonically less active than 5 Ma, predicted fault displacements are minor and will alter rock properties minimally compared to intact host rock alterations due to the cumulative fault displacements of an active tectonic past. Furthermore, flow and transport in the SZ are dominated by existing fractures, fracture clusters, and fracture spacing collectively labeled as flowing intervals in the SZ flow and transport model (BSC 2005 [DIRS 174012], Section 6.5.2.4). The SZ flow and transport model evaluates uncertainties assigned to flowing interval properties, such as HAVO, flowing interval spacing, FPVO in the volcanics, and longitudinal dispersion (BSC 2005 [DIRS 174012], Table 6-8). Transport times through the SZ are quite sensitive to parameter uncertainty associated with flowing interval properties; only the uncertainty incorporated in the specific discharge scaling parameter meant to account for increased infiltration, and a rise in the water table due to a wetter climate, produces a greater variation in transport times. As an example, parameter uncertainty in flowing interval spacing results in transport times that vary by several thousands of years (Arnold et al. 2000 [DIRS 166335]). The uncertainty incorporated in the horizontal anisotropy (partially a function of maximum and minimum in situ stresses imposed on fracture and fault orientations (Faunt 1997 [DIRS 100146] and BSC 2004 [DIRS 170010], Section 6.2.6) results in the suite of transport paths varying by several kilometers from one another (BSC 2005 [DIRS 174012], Figurer 6-6). Thus, the incorporated parameter uncertainty in regional flowing interval properties overwhelms any changes in SZ transport times and flow paths associated with seismically induced changes in hydrologic properties of the rock matrix, inclusive of the Bow Ridge fault in the Imbricate Fault Zone and the Solitario Canyon fault (see related FEPs 1.2.10.01.0A–Hydrologic response to seismic activity, 2.2.06.02.0A–Seismic activity changes porosity and permeability of faults, and 2.2.06.02.0B–Seismic activity changes porosity and permeability of fractures).

In summary, the expected changes in rock properties due to seismic activity are excluded based on low consequence because they will not significantly change radiation exposure to the RMEI or radionuclide releases to the accessible environment.

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.17 Seismic Activity Changes Porosity and Permeability of Faults (2.2.06.02.0A)

FEP Description: Seismic activity (fault displacement or vibratory ground motion) has a potential to produce jointed-rock motion and change stress and strains that alter the permeability along faults. This could result in reactivation of pre-existing faults or generation of new faults, which could significantly change the flow and transport paths, alter or short-circuit the flow paths and flow distributions close to the repository, and/or create new pathways through the repository. These effects may decrease the transport times for potentially released radionuclides.

Screening Decision: Excluded–Low consequence

Screening Argument:

Fault displacement is a result of regional plate tectonic activity that imparts crustal extension stresses causing rupture of the parent rock. Within the Basin and Range Province (which includes the Yucca Mountain region) peak extension stresses occurred between 10 and 12 Ma with extension rates between 10 and 30r mm/year (National Research Council 1992 [DIRS 105162], Chapter 2). These rapid extension rates formed two major north trending extension belts and normal faulting zones. Approximately 5 Ma, regional extensional stress declined to 5 to 10 mm/year; extension rates are still in a declining state today (National Research Council 1992 [DIRS 105162], Chapter 2). It is the extensional stresses imposed on the areally broad Basin and Range Province that impart the extension, compression, and shear stresses on the crust and determine fault development. The type of stress transmitted locally is dependent on location, depth, and juxtaposition to existing faults. These locally imposed stresses, which control existing fault hydrological properties (BSC 2004 [DIRS 170037], Section 6.3.2.10), are driven by the crustal (and now declining) extension rates. Concurrent with declining extension rates are declining fault and fracture development and fault displacement. Of interest is the likelihood of future fault formation and displacement within the Yucca Mountain region.

Expert elicitation, documented in the PSHA report (CRWMS M&O 1998 [DIRS 103731], Section 4), provides information that can be used to assess the effects of a seismic event on fault formation. As part of the PSHA, six teams of experts evaluated the available data to assess the fault displacement potential for 9 sites that represent the range of fault conditions in the Yucca Mountain vicinity (CRWMS M&O 1998 [DIRS 103731], Figure 4-9). The teams also characterized the uncertainty in their assessment by defining alternative models and approaches and assigning them weights. For each combination of alternatives, results for each site were provided as the annual frequency with which given levels of fault displacement would be exceeded. Uncertainty in the results was characterized by calculating the mean hazard and various percentile values. Results for each team were then combined using equal weights to determine the integrated fault displacement hazard (CRWMS M&O 1998 [DIRS 103731], Sections 4 and 8). The PSHA group assessed the mean displacement in intact host rock to be less than the 0.1 cm for a 1×10^{-8} annual-exceedance probability (CRWMS M&O 1998, [DIRS 103731, Section 8.2.1). Consequently, no significant new faults are likely to form in the Yucca Mountain vicinity within the next 10,000 years.

A seismic event is most likely to cause movement along existing faults and could affect a fault's hydrologic properties. Excluding the Solitario Canyon and Bow Ridge faults, the range of the expert teams' results for intrablock fault displacement, taking into account alternative approaches, varies between approximately 0.1 – 4.5 m at an annual-exceedance probability of 1×10^{-8} (CRWMS M&O 1998 [DIRS 103731], Figures 8-17 to 8-27). This is taken as the upper limit for faults within the Yucca Mountain region. Incorporating the weights for each team's alternative approaches and combining the results for all six teams using equal weight, the 'integrated' mean displacement hazard varies from less than 0.1 m to approximately 2.5 m (CRWMS M&O 1998 [DIRS 103731], Figures 8-4 to 8-12).

The exceptions to this displacement range are the predicted displacements for the Solitario Canyon and Bow Ridge faults (CRWMS M&O 1998 [DIRS 103731], Sites 2 and 1 in Figure 4-9), which are block-bounding faults and are expected to have higher displacements. Extrapolating the PSHA results out to the annual exceedance probability of 1×10^{-8} results in a 13 m approximate mean displacement for the Solitario Canyon fault and a 6 m approximate mean displacement for the Bow Ridge fault (CRWMS M&O 1998 [DIRS 103731], Figure 8-2 and 8-3).

As suggested in *Features, Events and Processes: Disruptive Events* (BSC 2005 [DIRS 173981], Section 6.2.1.10), the strain produced from a seismic event will be dissipated along existing faults. This strain can cause deformation and breakage of the parent rock, creating brecciation and gouge zones adjacent to the faults and existing fractures and possibly the production of new fractures (outside of the brecciated zone). This disturbed rock zone, labeled herein as a "zone of alteration," is correlated with the amount of fault offset (Sweetkind et al. 1997 [DIRS 100183]). Generally, the zone of alteration adjacent to the fault is relatively narrow. Faults with 1 to 5 m of cumulative offset have a zone of alteration width of only 1 m; faults with tens of meters of offset can have a zone of alteration up to 10 meters wide (Sweetkind et al. 1997 [DIRS 100183], pp. 66 to 71).

Several studies have been performed to determine changes in water table elevations due to seismically induced changes in fault properties, implicitly due to fault offset. Carrigan et al. (1991 [DIRS 100967]) modeled a 100 m wide fracture zone centered on a vertical fault (i.e., a seismically induced altered zone), such that vertical permeability was increased by three orders of magnitude. The results of that model indicate (a short-term) transient water table rise of up to 12 m in the fracture zone with 1 m of fault slip. Their tectonohydrologic model simulated earthquakes typical of the Basin and Range Province (with approximately a 1 m slip) to produce a simulated rise of 2 to 3 m for a water table 500 m below ground surface. Extrapolation to a 4 m slip results in a transient rise of 17 m near the fault (Carrigan et al. 1991 [DIRS 100967], p. 1159).

Gauthier et al. (1996 [DIRS 100447], pp. 163 to 164) analyzed the potential changes in water table elevation due to the effects of seismic activity as a result of three different types of fault displacements. For all three fault types, a 1 m displacement with a 30 km rupture length was considered. Simulations of the timing, magnitude, and duration of water table rise indicate a maximum rise of 50 m within an hour of the simulated event. The simulated system returns to steady-state conditions within six months. Gauthier et al. (1996 [DIRS 100447]) concluded that:

> In general, seismically induced water table excursions caused by poroelastic coupling would not influence the models presently being used to determine long-term performance of a repository at Yucca Mountain; therefore, they were excluded from the total-system simulation.

The above studies predict short-term water table excursion, given 1–4 m fault slips. It is inferred that an approximately 13 m displacement along the Solitario Canyon fault will result in transient and slightly higher water table excursions. These early studies substantiate an investigation headed by the National Research Council (1992 [DIRS 105162], Chapter 5) on the geologic and climatic processes that could affect water table elevations. The council addressed the maximum level the water table could rise within the next 10,000 years, given several processes, one being seismic pumping. (Seismic pumping is a transient water table rise as a result of a seismic event.) They evaluated water table responses due to two types of seismic processes: (1) dislocation, where zones of extension on one side of a fault are balanced by compression across the fault; and (2) the more realistic "changes in regional stress" approach caused by normal fault slippage in regions of extension. The regional stress approach evaluates the effect of stress on pore pressure, which is dependent upon the elastic properties of the bulk rock and the mineral grains. The extent of water table fluctuations differed for both models. Adopting the dislocation model, the water table rose approximately 10 m. Adopting the regional stress approach resulted in maximum water table rise of 50 m. The latter approach assumes realistically conservative rock and mineral elastic properties. The panel concluded, regardless of the approach taken, that the maximum water table rise, given a seismic event, would be less than 50 m and transient in nature. Because water table fluctuations were transient for both modeling approaches, a future seismic event (predicted over the next 10,000 years) that could result in a 10 m slip along the Solitario Canyon fault will not alter the fault's hydrologic properties.

Moreover, current Solitario Canyon fault hydrologic properties reflect the cumulative effects of a active tectonic and seismic past that resulted in a 260 m cumulative fault displacement where it intersects the ECRB Cross-Drift (Mongano et al. 1999 [DIRS 149850], pp. 48 to 65). With this relatively large fault displacement, its zone of alteration consists of an approximate 20 m brecciated and gouge zone (Mongano et al. 1999 [DIRS 149850], pp. 59-65). An approximately 13 m displacement of the Solitario Canyon fault (and other faults) will release local stresses accumulated along the fault plane but will not alter the large and globally extensive stresses in effect over the past 10-12 million years incurred in the parent rock and embedded faults within the Yucca Mountain region (National Research Council 1992 [DIRS 105162], Chapter 5). It is these global and areally extensive stresses imposed on the fault that determine the hydrologic properties of the fault, such as permeability and porosity. The logical conclusion is that the Solitario Canyon fault's hydrologic properties will remain essentially unchanged, given an approximate 13 m displacement. The fault will continue to serve as a groundwater divide between the Yucca Mountain and the Crater Flat regions (BSC 2004 [DIRS 170037], Section 6.3.2.3). As observed with other fault displacements, the water table could rise or decrease due to seismic response, but the fluctuation will be (at most) a few tens of meters and transient in nature.

The magnitude and transient nature of a predicted water table rise is consistent with observation of recorded seismic events. O'Brien (1993 [DIRS 101276]) analyzed water table level fluctuations at Yucca Mountain due to earthquakes. Water table fluctuations range from 90 cm, related to a 7.5 magnitude earthquake near Landers, California (approximately 420 km from Yucca Mountain), to 20 cm for a second quake of 6.6 magnitude near Big Bear Lake, California (approximately 400 km from Yucca Mountain). More notably, a 5.6 magnitude quake at Little Skull Mountain (approximately 23 km from Yucca Mountain) resulted in a maximum fluctuation of 40 cm, with water levels in another well declining approximately 50 cm over the three days following the earthquake. Water levels in that well returned to prequake levels over a period of about six months. The above reports support the fact that recorded fault slippage in the Yucca Mountain region has resulted in a transient hydrologic response but has not resulted in permanent alteration of the fault's regional hydrologic properties, and, by implication, regional flow paths.

Additionally, the uncertainty in the effective hydrologic properties incorporated in the SZ flow and transport model (BSC 2005 [DIRS 174012], Table 6-8), which reflects the cumulative changes in a fault's hydrologic properties during a heightened seismically active past, coupled with the scale of the model (a grid discretized 500 m in the horizontal direction and 10–550 m in the vertical direction), overwhelms the changes in fault properties, and their effects on flow paths and transport times, that would be caused by seismic events within the next 10,000 years. Flow and transport in the SZ is dominated by existing fractures, fracture clusters and fracture spacing collectively labeled as flowing intervals in the SZ flow and transport model (BSC 2005 [DIRS 174012], Section 6.5.2.4). The SZ flow and transport model evaluates uncertainties assigned to flowing interval properties, such as HAVO, flowing interval spacing, FPVO in the volcanic units, and longitudinal dispersion (BSC 2005 [DIRS 174012], Table 6-8). Transport times through the SZ are quite sensitive to parameter uncertainty associated with flowing interval properties (only uncertainty in the specific discharge scaling parameter, which is meant to account for increased specific discharge due to a wetter climate, produces a greater variation in transport times). As an example, parameter uncertainty for flowing interval spacing results in transport times that vary by several thousands of years (Arnold et al. 2000 [DIRS 166335]). The uncertainty incorporated in the horizontal anisotropy (which accounts for the uncertainty in maximum and minimum in situ stresses imposed on fractures and faults) results in transport paths varying by several kilometers (BSC 2005 [DIRS 174012], Figure 6-6). Thus, the incorporated parameter uncertainty in regional flowing interval properties overwhelms any potential changes in a fault's hydrologic properties associated with future seismic activity (which is reflective of regional tectonic activity).

Consequently, future seismic events will not alter the range of existing fault permeability and porosity values incorporated in the SZ flow and transport model. See related FEPs 1.2.10.01.0A-Hydrologic response to seismic activity and 2.2.06.02.0B–Seismic activity changes porosity and permeability of fractures.

In summary, seismic events will have a minimal effect on the simulated flux at the compliance boundary, and on the release of radionuclides to the accessible environment based on the following conclusions:

1. Future seismic events are expected to rupture existing faults, rather than developing new faults.

2. Changes to fault properties (which implicitly affect the fault's hydrologic properties) will tend to occur in a relatively narrow zone, and be on the order of a few meters to, at most, tens of meters wide along the length of the fault (BSC 2005 [DIRS 173981], Section 6.2.1.10).

3. Current fault porosities and permeabilities reflect the effects of a seismically active past within the Yucca Mountain region. Past seismic activity is reflective of major plate extension and caldera formation phases in the Basin and Range Province, which includes the Yucca Mountain region. Seismic activity within the Yucca Mountain region is currently occurring at a reduced level relative to the period of most active extension 10 to 12 million years ago. Consequently, seismic events that will occur in the next 10,000 years will have a "relatively" low impact on existing fault hydrologic properties.

4. The uncertainty in the effective hydrologic properties incorporated in the SZ flow and transport model, coupled with the flux multiplier that effectively models wetter climatic conditions, overwhelms the changes that would be caused by small movements along existing faults.

5. Observed, seismically induced water table fluctuations, and those simulated with numerical models, indicate future seismic events will alter water table elevations for a relatively short period of time.

In conclusion, changes in fault properties in the SZ can be excluded based on low consequence because they will not significantly affect radiation exposure to the RMEI or radionuclide releases to the accessible environment.

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.18 Seismic Activity Changes Porosity and Permeability of Fractures (2.2.06.02.0B)

FEP Description: Seismic activity (fault displacement or vibratory ground motion) has a potential to change stress and strains that alter the permeability along fractures. This could result in reactivation of pre-existing fractures or generation of new fractures, which could significantly change the flow and transport paths, alter or short-circuit the flow paths and flow distributions close to the repository, and/or create new pathways through the repository. These effects may decrease the transport times for potentially released radionuclides.

Screening Decision: Excluded–Low consequence

Screening Argument:

Fault displacement, and concomitant fracture formation, is a result of regional plate tectonic activity that imparts crustal extensional stresses causing rupture of the parent rock. Within the Basin and Range Province (which includes the Yucca Mountain region), peak extensional stresses were 10-30 mm/year between 10 and 12 Ma (National Research Council 1992 [DIRS 105162], Chapter 2). These rapid extension rates formed two major north trending extension belts and normal faulting zones. Approximately 5 Ma, regional extensional stress declined to 5-10 mm/year; extension rates are still in a declining state today (National Research Council 1992 [DIRS 105162], Chapter 2). It is the extension stresses of the areally broad Basin and Range Province that impart the extension, compression, and shear stresses on the crust and determine fault and concomitant fracture development and properties. The type of stress transmitted locally is dependent on location, depths, and juxtaposition to existing faults. These locally imposed stresses, which control existing fault hydrological properties (BSC 2004 [DIRS 170037], Section 6.3.2.10), are driven by the crustal (and now declining) extension rates. Concurrent with declining extension rates are declining fault and fracture development, and fault displacement. Of interest is the likelihood of fracture formation within the Yucca Mountain region.

Expert elicitation, documented in the Probabilistic Seismic Hazard Analysis (PSHA) report (CRWMS M&O 1998 [DIRS 103731], Sections 4 and 8), provides information that can be used to assess the effects of a seismic event on the hydrologic properties of faults and the host rock. As part of the PSHA, six teams of experts evaluated the available data to assess the fault displacement potential for 9 sites that represent the range of fault conditions in the Yucca Mountain vicinity (CRWMS M&O 1998 [DIRS 103731], Figure 4-9). The teams also characterized the uncertainty in their assessment by defining alternative models and approaches and assigning them weights. For each combination of alternatives, results for each site were provided as the annual frequency with which given levels of fault displacement would be exceeded. Uncertainty in the results was characterized by calculating the mean hazard and various percentile values. Results for each team were then combined using equal weights to determine the integrated fault displacement hazard (CRWMS M&O 1998 [DIRS 103731], Sections 4 and 8). PSHA expert group predicts less than a 0.1-cm displacement within intact host rock (between Solitario Canyon and the Ghost Dance faults) at a 1×10^{-8} exceedance probability (CRWMS M&O 1998 [DIRS 103731], Section 8.2.1). Consequently, no significant new faults and fractures are likely to form in the Yucca Mountain vicinity within the next 10,000 years.

Furthermore, future seismic events are expected to rupture existing faults, rather than developing new faults. Excluding the Solitario Canyon and Bow Ridge faults, the range of the expert teams' results for intrablock fault displacement, taking into account alternative approaches, varies between approximately 0.1 – 4.5 m, at an annual-exceedance probability of 1×10^{-8} (CRWMS M&O 1998 [DIRS 103731], Figures 8-17 to 8-27). This is taken as the upper limit for faults within the Yucca Mountain region. Incorporating the weights for each team's alternative approaches and combining the results for all six teams using equal weight, the 'integrated' mean displacement hazard varies from less than 0.1 m to approximately 2.5 m (CRWMS M&O 1998 [DIRS 103731], Figures 8-4 to 8-12).

The exceptions to this displacement range are the predicted displacements for the Solitario Canyon and Bow Ridge faults (CRWMS M&O 1998 [DIRS 103731], Sites 2 and 1 in Figure 4-9), which are block-bounding faults and are expected to have higher displacements. Extrapolating the PSHA results out to the annual exceedance probability of 1×10^{-8} results in a 13 m approximate mean displacement for the Solitario Canyon fault and a 6 m approximate mean displacement for the Bow Ridge fault (CRWMS M&O 1998 [DIRS 103731], Figure 8-2 and 8-3).

As discussed in *Features, Events and Processes: Disruptive Events* (BSC 2005 [DIRS 173981], Section 6.2.1.10), the strain produced from a seismic event will be dissipated along existing faults. Changes in rock properties along the length of existing faults, due to the creation of brecciation and gouge zones adjacent to the fault and the production of fractures (outside of brecciated zone), are correlated with the amount of fault offsets (Sweetkind et al. 1997 [DIRS 100183]). Generally, the zone of increased fracturing adjacent to the fault is relatively narrow. Faults with 1–5 m of cumulative offset have a zone of fracturing of only 1–2 m; faults with tens of meters of offset can have zone of fracturing up to ten meters wide (Sweetkind et al. 1997 [DIRS 100183], pp. 66 through 71). The Solitario Canyon fault has a cumulative displacement of approximately 260 m where it intersects the ECRB Cross-Drift; with this relatively large displacement, its zone of alteration consists of approximately a 20 m brecciated and gouge zone and seismically induced fractures that extend tens of meters from the fault (Mongano et al. 1999 [DIRS 149850], pp. 59-65). Several studies have been performed to determine changes in water table elevations due to seismically induced changes in fault and fracture properties. Brief summaries of their findings follow.

Carrigan et al. (1991 [DIRS 100967]) modeled a 100 m-wide fracture zone centered on a vertical fault, such that vertical permeability was increased by three orders of magnitude. The results of that model indicate a transient water table rise of up to 12 m in the fracture zone accompanying one meter of fault slip (the rise labeled as seismic pumping). The Carrigan study predicts short-term water table excursions given 1–4 m fault slips and attendant alteration of adjacent fractures. It is inferred that an approximate 13 m displacement along the Solitario Canyon fault, and resulting changes in fracture properties, will result in transient and slightly higher water table excursions. This assumption is supported by an investigation headed by the National Research Council (National Research Council 1992 [DIRS 105162]) on the geologic and climatic processes that could affect water table elevations.

The National Research Council addressed the maximum level the water table could rise within the next 10,000 years, as a result of several processes, including seismic pumping. They evaluated water table responses due to two types of seismic processes: (1) dislocation, where zones of extension on one side of a fault are balanced by compression across the fault; and (2) the more realistic "changes in regional stress" approach caused by normal fault slippage in regions of extension. The regional stress approach evaluates the effect of stress on pore pressure, which is dependent upon the elastic properties of the bulk rock and the mineral grains. The extent of water table fluctuations differed for both models. By adopting the dislocation model, the water table rose approximately 10 m. Adopting the regional stress approach resulted in maximum water table rise of 50 m. The latter approach assumes realistically conservative rock and mineral elastic properties. The panel concluded that, regardless of what approach is taken, the maximum water table rise, given a seismic event, would be less than 50 m and transient in nature. Because water table fluctuations were transient for both modeling approaches, it is inferred that a future seismic event (predicted over the next 10,000 years) that could result in changes in the regional stress field imposed on fractures, inclusive of stresses imposed by a 10 m slip along the Solitario Canyon fault, will not alter the regional fracture hydrologic properties. Adjustments to stresses will occur abruptly, along existing strike-slip fault zones as young's modulus of the rock is exceeded. These abrupt redistributions of the stress field will cause earthquakes and transient rise in water table along and adjacent to existing faults, due to pore and grains being compressed/rearranged as their elastic strength is exceeded. This redistribution of pressure on the material properties is transient in nature and is a result of the steady but declining extensional stresses imposed on the region. These studies suggest seismic pumping due to changes in fracture permeability along faults would produce a short-term and transient water table rise.

The magnitude and transient nature of a predicted water table rise is consistent with observations of water table fluctuations, given seismic events. O'Brien (1993 [DIRS 101276]) analyzed water table fluctuations at Yucca Mountain due to earthquakes. Water table fluctuations range from 90 cm, related to a 7.5 magnitude earthquake near Landers, California (approximately 420 km from Yucca Mountain), to 20 cm for a second quake of 6.6 magnitude near Big Bear Lake, California (approximately 400 km from Yucca Mountain). More notably, a 5.6 magnitude quake at Little Skull Mountain (approximately 23 km from Yucca Mountain) resulted in a maximum fluctuation of 40 cm at one well, while water levels in another well declined approximately 50 cm over the three days following the earthquake. Water levels in that well returned to prequake levels over a period of about six months. Given the observed transient responses to seismic events within the southwest portion of the Basin and Range Province, it is inferred that the above seismic events did not alter regional fracture hydrologic properties.

Additionally, flow and transport in the SZ is dominated by existing fractures, fracture clusters, and fracture spacing collectively labeled as flowing intervals in the SZ flow and transport model (BSC 2005 [DIRS 174012], Section 6.5.2.4). The SZ flow and transport model evaluates uncertainties assigned to flowing interval properties, such as HAVO, flowing interval spacing, FPVO in the volcanic units, and longitudinal dispersion (BSC 2005 [DIRS 174012], Table 6-8). Transport times through the SZ are quite sensitive to parameter uncertainty associated with flowing interval properties. Only uncertainty in the specific discharge scaling parameter, which is meant to account for increased specific discharge due to a wetter climate, produces a greater variation in transport times. As an example, parameter uncertainty in flowing interval spacing results in transport times that vary by several thousands of years (Arnold et al. 2000 [DIRS 166335]). The uncertainty incorporated in the horizontal anisotropy (which accounts for the uncertainty in maximum and minimum in situ stresses imposed on fractures and faults) results in transport paths varying by several kilometers (BSC 2005 [DIRS 174012], Figure 6-6). Thus, the incorporated parameter uncertainty in regional flowing interval properties overwhelms any changes in SZ transport times and flows paths associated with seismically induced changes in flowing interval properties.

Furthermore, existing regional stresses imposed on fracture hydrologic properties reflect the crustal extension stresses in effect today. A fracture's physical properties (orientation, length, connectivity, and clustering) are reflective of a cumulative response to seismic events in existence 10–12 Ma. A change in regional fracture properties, given predicted seismic activity, will be minimal relative to multiple seismic events imposed in the region for many millennia. Therefore, it is inferred that regional fracture hydrologic properties will not be significantly altered from current conditions in the next 10,000 years. As a result, changes in intact fracture properties, resulting from seismic activity, are excluded based on low consequence because they will not significantly affect radiation exposure to the RMEI or radionuclide releases to the accessible environment.

Additional discussions on the effects of seismic events on rock properties are provided in *Features, Events, and Processes: Disruptive Events* (BSC 2005 [DIRS 173981], Sections 6.2.1.8, 6.2.1.9, 6.2.1.10, and 6.2.1.11).

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.19 Saturated Groundwater Flow in the Geosphere (2.2.07.12.0A)

FEP Description: Groundwater flow in the saturated zone below the water table may affect long-term performance of the repository. The location, magnitude, and direction of flow under present and future conditions and the hydraulic properties of the rock are all relevant.

Screening Decision: Included

Screening Argument: N/A

TSPA Disposition:

Steady-state, saturated, three-dimensional groundwater flow within the Yucca Mountain vicinity is modeled in the *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037], Section 6.1 and 6.3.1) and the *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036], Section 6.3) using the numerical code FEHM. The estimated groundwater flow rates into the SZ site-scale flow model domain, both as recharge (infiltration) at the upper boundary (water table) and as underflow at the lateral boundaries, are determined from a larger scale regional model and reported in *Recharge and Lateral Groundwater Flow Boundary Conditions for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2004 [DIRS 170015], Section 6) and a much smaller scale model, which calculates infiltration from the UZ to the SZ in the area of the repository footprint (BSC 2004 [DIRS 170015] Section 6.2.2). The site-scale model domain is a 30 km by 45 km region within the confines of the Death Valley groundwater basin (BSC 2004 [DIRS 170037], Section 6.3.2 and Figure 6-1). Inputs include faults and fault zones (BSC 2004 [DIRS 170037], Section 6.3.2.10), and variable permeabilities associated with the 19 hydrostratigraphic units (FEP 2.2.03.02.0A–Rock properties of host rock and other units) identified through the hydrogeologic framework used in the base-case flow model (BSC 2005 [DIRS 174109]). The most significant flow units are the volcanic Crater Flat Tuff hydrogeologic (hydraulic) units and the shallow alluvial aquifer of Fortymile Wash. As discussed in the report *Probability Distribution for Flowing Interval Spacing* (BSC 2004 [DIRS 170014]), only a subset of existing fractures is observed to transmit flow in the SZ. Flow through fractures is modeled through an effective continuum flow model (BSC 2004 [DIRS 170037], Section 6.3.3).

Uncertainty in the saturated flow through fractures is incorporated in the flow modeling with parameters of flowing interval spacing, specific discharge, and the horizontal anisotropy (BSC 2005 [DIRS 174012], Sections 6.5.2.1, 6.5.2.4, and 6.5.2.10). Uncertainty in groundwater specific discharge in the alluvium is discussed in *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010], Section 6.5.5).

Recharge is modeled through underflow, surface flow infiltration, and UZ infiltration components. More specifically it includes distributed vertical recharge from the regional-scale groundwater flow model, recharge from infiltration of surface water flows in Fortymile Wash, and recharge from the UZ site-scale flow model. The UZ infiltration components include an area outside of the repository footprint (defined as the distributed UZ infiltration component), and infiltration from the more refined discretized area of the repository footprint (BSC 2004 [DIRS 170037], Section 6.3.2.7). The impact of future climatic conditions on flow are modeled in the *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012], Sections 6.5) using a convolution integral method (SNL 2003 [DIRS 163344]) that scales radionuclide BTC simulations representing current climatic conditions with future climate state scaling factors (BSC 2005 [DIRS 174012], Section 6.5).

Supporting Reports:

- *Recharge and Lateral Groundwater Flow Boundary Conditions for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2004 [DIRS 170015])
- *Probability Distribution for Flowing Interval Spacing* (BSC 2004 [DIRS 170014])
- *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037])
- *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036])
- *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012])
- *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010]).

6.2.20 Water-Conducting Features in the SZ (2.2.07.13.0A)

FEP Description: Geologic features in the saturated zone may affect groundwater flow by providing preferred pathways for flow.

Screening Decision: Included

Screening Argument: N/A

TSPA Disposition:

Faults and fractures in the volcanic units are explicitly modeled in the SZ (BSC 2005 [DIRS 174012]) through 17 discrete geologic features incorporated in the SZ base-case model (BSC 2004 [DIRS 170037], Section 6.5.3.4). The impacts of these various features on SZ transport are evaluated in *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036], Sections 6.3 and 6.4). The variability and uncertainty due to the presence of fracture clusters, flowing intervals, and rubblized zones (all possible subsets of water-conducting features within the faulted and fractured system) are modeled in the SZ transport abstraction model and the SZ one-dimensional transport model, both described in *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]). The variability and uncertainty are represented through the following stochastically sampled parameters: GWSPD, FISVO, HAVO, FPVO, and LDISP, as shown in Section 6.5.2 and Table 6-8 of the SZ flow and transport model abstraction (BSC 2005 [DIRS 174012]). The ranges of uncertainty in these parameters encompass the possibility of channelized flow along preferred pathways. The parameters are described in Sections 6.5.2.1, 6.5.2.4, 6.5.2.5,6.5.2.9, and 6.5.2.10 of the abstraction.

Numerous broad and distinct zones in the SZ flow model are categorized as features and, depending upon their physical properties, these act as either barriers or conduits to SZ groundwater flow. These areas are directly or indirectly affected by faults, zones of mineralogical alteration along faults, or contact zones between units (BSC 2004 [DIRS 170037], Section 6.5.3.4). In total, there are 17 features defined in the SZ site-scale flow model for Yucca Mountain.

A feature with no known association with a distinct fault or fault zones is also incorporated into the SZ flow and transport model and is based on a large hydraulic gradient, which exists just north and slightly west of Yucca Mountain. There are several theories as to the cause of the large hydraulic gradient, but no one theory is overwhelmingly favored over others. Nevertheless, this feature has been incorporated into the model to produce a large hydraulic gradient north of the repository through a low-permeability east-west feature north of Yucca Mountain, see Zone 56 in Figure 6.2-3 (BSC 2004 [DIRS 170037], Section 6.8.1).

All 17 features are distinct from the subhorizontal geologic formations of the hydrogeologic framework model (BSC 2005 [DIRS 174109]) in which they reside; most are essentially vertical, with some linear in the horizontal extent, and others areally extensive (BSC 2004 [DIRS 170037], Figure 6-37). Depending upon their hydrologic impact on groundwater flow patterns, these features fall under several distinct categories as follows: (1) zones of permeability enhancement parallel to faults and zones of permeability reduction perpendicular to faults; (2) fault zones with enhanced permeability; (3) contact zones between units and nonfault zones; (4) features, some bordered by faults, representing regions of lower permeability caused by hydrothermal alteration and; (5) zones of unknown features (*Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037], Table 6-17). A list of the 17 features modeled in *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037], Table 6-17), aggregated under hydrologic characteristics, is given in the supplemental discussion.

Smaller-scale water conducting features are assessed as flowing intervals in the fractured volcanic units, as described in *Probability Distribution for Flowing Interval Spacing* (BSC 2004 [DIRS 170014]). In situ testing of smaller scale water conducting features was performed at the C-wells complex, as documented in *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010]).

Supporting Reports:

- *Hydrogeologic Framework Model for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2005 [DIRS 174109])
- *Probability Distribution for Flowing Interval Spacing* (BSC 2004 [DIRS 170014])
- *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037])
- *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036])
- *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012])
- *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010]).

Supplemental Discussion:

In Figure 6.2-3, a depiction of the 17 discrete features is modeled in the SZ flow and transport model and described in detail in the *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037], Table 6-17). Many of these features are based on known faults and fault zones depicted on the left side of the figure.

(1) Zones of permeability enhancement parallel to faults and zones of permeability reduction perpendicular to faults

- **Crater Flat Fault**–This is a linear feature running north-south in the western half of the model, starting south of Claim Canyon and terminating near Highway 95, almost halfway between the western boundary of the Solitario Canyon and the SZ site-scale model domain. Vertically, it extends from the top to the bottom of the model.
- **Solitario Canyon Fault Zone**–This is a north-south trending linear feature just to the west of Yucca Mountain. Vertically, it extends from the top to the bottom of the model.
- **Solitario Canyon Fault, East Branch**– This is a north-northeast trending linear feature just to the east of Yucca Mountain. Vertically, it extends from the bottom to the top of the model.
- **Solitario Canyon Fault, West Branch**– This is a north-northeast trending linear feature just to the west of Yucca Mountain. Vertically, it extends from the bottom to the top of the model.
- **Highway 95 Fault (West)**–This is a linear feature in the lower half of the western portion of the model. It is east-southeast trending. Vertically, it extends from the bottom to the top of the model.

(2) Fault zones with enhanced permeability

- **Bare Mountain Fault**–This is a northwest- to southeast-trending linear feature in the southwestern corner of the model. Vertically, it extends from the bottom to the top of the model.

- **Imbricate Fault Zone**–This is a highly faulted area bounded in the west by the Ghost Dance fault, to the south by the Dune Wash, to the east by the Paintbrush Canyon fault, and to the north by the Drill Hole Wash. Vertically, it extends from the top of the model down through the middle volcanic units to the top of the undifferentiated units.

(3) Contact zones between units and nonfault zones

- **Alluvial Uncertainty Zone**–This feature represents the uncertainty zone between the alluvium and tuff boundaries. It is roughly a rectangular region to the south of Yucca Mountain in the southern half of the model. Vertically, it extends from the top of the model down through the undifferentiated units.

- **Spotted Range-Mine Mountain Zone**–This triangular feature is in the southeast corner of the model. Vertically, it extends from top of the model down to the bottom. A zone of enhanced permeability is associated with the Spotted Range Thrust Region.

- **Fortymile Wash Zone**–This north-south linear feature is located approximately halfway between Yucca Mountain and the eastern model boundary. Vertically, it extends from the top to the bottom of the model.

- **Lower Fortymile Wash Zone**–This quadrilateral, enhanced permeability feature encompasses the Lower Fortymile Wash part of the model. The depth of the zone includes the alluvium unit to the top of the model.

(4) Zones representing regions of lower permeability caused by hydrothermal alteration

- **Northern Zone (entire Claim Canyon, Calico Hills, and Shoshone Mt.)**–This zone is wedge-shaped, spanning almost the entire northern boundary (except the western corner of the northern boundary) and, approximately, the upper fourth of the eastern boundary. Vertically, it extends from the top to the bottom of the model.

- **Northern Crater Flat Zone**–This wedge-shaped zone is at the northern third of the western boundary of the model. Vertically, it extends from the top to the bottom of the model.

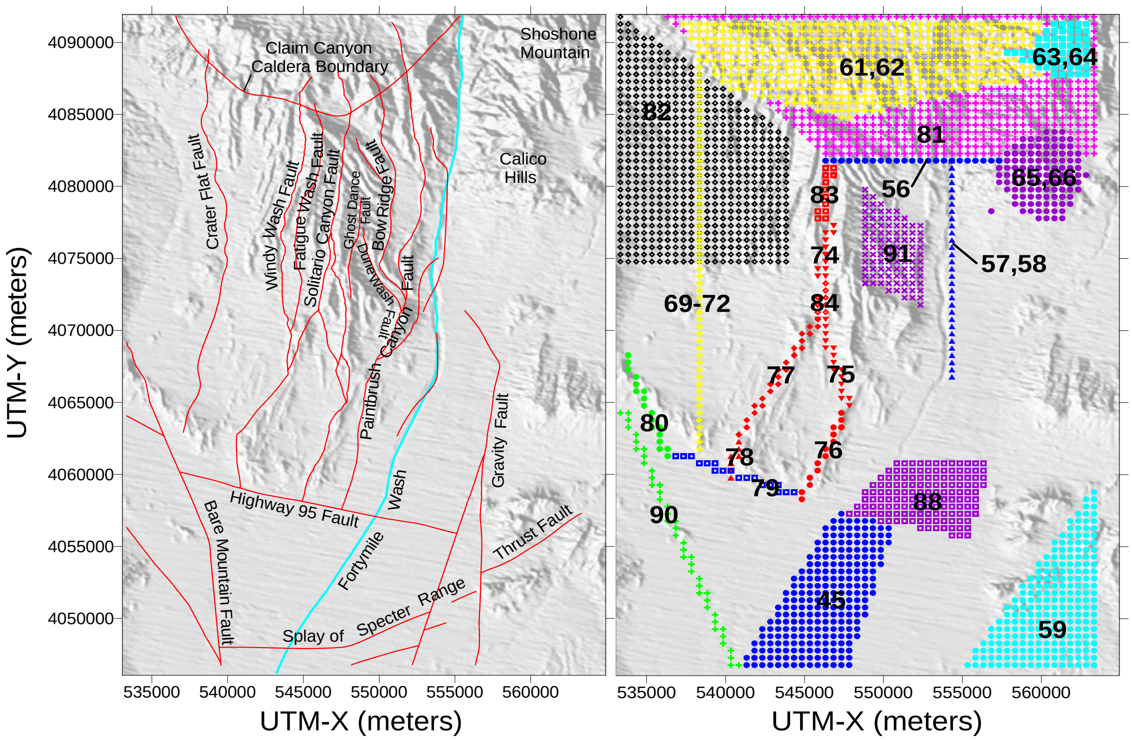
- **Claim Canyon Caldera**–This zone spans much of the northern boundary of the model, extending south as triangular shapes and terminating north of the Yucca Wash. Vertically, it extends from the top to the bottom of the model.

- **Shoshone Mt. Zones**– These zones are in the northeastern corner of the model. They extend from the top of the carbonate aquifer up to the top of the model.

- **Calico Hills Zones**– These zones are near the eastern end of the model, south of the Shoshone Mountain Zones, at approximately the same northing as the Yucca Wash. Vertically, they extend from the top to the bottom of the model.

(5) Zones of unknown features

East-West Barrier–This linear feature runs east-west just to the north of Yucca Mountain, starting at the western edge of Yucca Mountain and extending eastwards short of the Calico Hills. Vertically, it extends from the bottom to the top of the model. It is a permeability reduction zone.



Source: Modified from BSC 2004 (DIRS 170037), Figures 6-37.

NOTE: Field data are on the left panel, and the SZ model representation is on the right panel. Numbers designate the following regions: 45 - Lower Fortymile Wash Zone; 56 - East-West Barrier Zone; 57 and 58 - Fortymile Wash Zones; 59 - Spotted Range-Mine Mountain Zone; 61 and 62 - Claim Canyon Caldera Zones; 63 and 64 - Shoshone Mountain Zones; 65 and 66 - Calico Hills Zones; 69, 70, 71, and 72 - Crater Flat Fault Zones; 74, 83, and 84 - Solitario Canyon Fault Zones; 75 and 76 - Solitario Canyon Fault Zones (East Branch); 77 and 78 - Solitario Canyon Fault Zones (West Branch); 79 -Highway 95 Fault Zone; 80 and 90 - Bare Mountain Fault Zones; 81 - Northern Zone; 82 - Northern Crater Flat Zone; 88 - Alluvial Uncertainty Zone (expected case); 91 - Imbricate Fault Zone.

Figure 6.2-3. Geologic Features in the Area of the Site-Scale Flow Model

6.2.21 Chemically-Induced Density Effects on Groundwater Flow (2.2.07.14.0A)

FEP Description: Chemically-induced spatial variation in groundwater density may affect groundwater flow.

Screening Decision: Excluded–Low consequence

Screening Argument:

The FEP is excluded based on the bounding and imposed condition that a contaminant plume reaches the water table with same density as that of in-situ waters, thus, not promoting flow due to density gradients. Density gradients due to the introduction of groundwater with higher solute concentration and higher density would spread the plume laterally in both the horizontal and vertical directions. Lateral spreading would expose the plume to more fracture-matrix interfaces in the volcanic units, thus, facilitating matrix diffusion. Additionally, more matrix diffusion means the plume is exposed to more sorption sites. These two processes enhance the plume's chemical (via sorption) and physical (via matrix diffusion) retardation, thus, increasing the plume's transport time to the accessible environment. Consequently, by not considering chemically induced density effects, the potential dose to the hypothetical exposed community is overestimated and the plume transport times are underestimated.

The TSPA-LA models calculate the concentration of contaminants in groundwater by capturing all of the contaminants that cross the regulatory boundary in the wells at the compliance point. No credit is taken for partial plume capture due to density-driven flow effects. The mixing model assumes that pumping and redistribution of well water will be far greater than any other energy gradients (e.g., thermal, chemical, and gravitational) that exist in the groundwater system. There is no modeled groundwater flow component resulting from buoyancy effects, or differences in the groundwater density due to the presence or absence of contaminants. The TSPA approach to dose modeling is predicated on the use of a prescribed volume of water. As long as that prescribed volume of water is defensible and consistent with regulations, by assuming that all the particles that cross the regulatory boundary are dissolved in the prescribed volume of groundwater (per guidance given in 10 CFR Part 63 Subparts and 63.312(c) 63.332 (a)(3) [DIRS 173273]), the potential dose to the hypothetical and exposed community will not be underestimated. Including chemically induced density effects into the TSPA-LA calculations would be beneficial to repository performance. Given that the volume of extracted water consumed is independent of density and thermal gradients, and all of the contaminants that cross the regulatory boundary are contained in that volume of water, the potential dose to the hypothetical and exposed community is overestimated rather than underestimated. Therefore, this FEP is excluded based on low consequence because it has no adverse effects on performance.

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.22 Advection and Dispersion in the SZ (2.2.07.15.0A)

FEP Description: Advection and dispersion processes may affect radionuclide transport in the saturated zone.

Screening Decision: Included

Screening Argument: N/A

TSPA Disposition:

Advection and longitudinal dispersion of dissolved radionuclides are explicitly included in the conceptual and mathematical models for TSPA-LA (BSC 2004 [DIRS 170036], Sections 6.3 and 6.4). The numerical code FEHM implements the dispersion tensor and random walk particle tracking method. The flow field and the dispersion tensor input to this model are dependent on the nature of the geologic material and the scale of the model. The estimated groundwater flow rates into the SZ site-scale flow model domain, both as recharge (infiltration) at the upper boundary (water table) and as underflow at the lateral boundaries, are determined from a larger scale regional model and reported in *Recharge and Lateral Groundwater Flow Boundary Conditions for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2004 [DIRS 170015], Section 6).

FEHM generates the three-dimensional flow field of the SZ site-scale flow model using calibrated permeability as input. The base-case specific discharge field is output from the *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037], Section 8.2). The base-case calibrated permeability field is scaled with the stochastically sampled GWSPD and HAVO (BSC 2005 [DIRS 174012], Sections 6.5.2.1 and 6.5.2.10) to produce 200 unique three-dimensional permeability fields. GWSPD scales permeabilities in both the volcanic and alluvium units. The range for the GWSPD scaling parameter is based on field-test analyses, discussed in *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010]); calibration of the "base-case" flow field to measured heads, discussed in *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037], Section 6.6.1.3); and expert elicitation, discussed in *Saturated Zone Flow and Transport Expert Elicitation Project* (CRWMS M&O 1998 [DIRS 100353], Section 3.2). The HAVO parameter determines the degree of anisotropy in permeability for only the volcanic units. HAVO is based on field-test analyses discussed in *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010], Section 6.2.6) and numerical analysis discussed in *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037], Section 6.5.3). Detailed discussions of the scaling parameters GWSPD and HAVO implementation are located in *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 ([DIRS 174012], Sections 6.5.2.1 and 6.5.2.10).

Uncertainty in the dispersion tensor is modeled by stochastically varying the input longitudinal dispersivity (LDISP) value. This approach is done using the LDISP (BSC 2005 [DIRS 174012], Section 6.5.2.9). The range for the LDISP parameter is based on recommendations from the expert elicitation panel (CRWMS M&O 1998 [DIRS 100353], Section 3.2), which were used as the basis for determining the bounds on the longitudinal dispersivity.

The transverse and vertical dispersion parameters are less than longitudinal dispersivity, not varied independently, and scaled based on the stochastically sampled LDISP value input to each flow field. Further discussions on transverse and vertical dispersion are located in *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012], Section 6.5.2.9).

Supporting Reports:

- *Recharge and Lateral Groundwater Flow Boundary Conditions for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2004 [DIRS 170015])
- *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037])
- *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036])
- *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012])
- *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010]).

6.2.23 Dilution of Radionuclides in Groundwater (2.2.07.16.0A)

FEP Description: Dilution due to mixing of contaminated and uncontaminated water may affect radionuclide concentrations in groundwater during transport in the saturated zone and during pumping at a withdrawal well.

Screening Decision: Included

Screening Argument: N/A

TSPA Disposition:

Dilution of radionuclides as a result of pumping is included in the TSPA-LA in two ways (BSC 2005 [DIRS 174012]). First, dilution of simulated radionuclide concentrations within the contaminant plume is explicitly modeled through the transverse hydrodynamic dispersion parameter and caused, in part, by heterogeneities in permeability at all scales (BSC 2004 [DIRS 170036], Section 6.4.2.1). Transverse dispersivity is a function of the stochastically sampled LDISP (BSC 2005 [DIRS 174012], Sections 6.7.2 and 6.5.2.9). Secondly, it is assumed in *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012], Sections 5 (3) and 6.3.3) that all of the radionuclide mass crossing the 18-km regulatory boundary is dissolved in the representative volume of water per 10 CFR Part 63 Subparts 63.312(c) and 6 3.332(a)(3) [DIRS 173273], 3,000 acre-ft per year (about 3.7×10^9 L). Therefore, the radionuclide mass that arrives at the 18-km boundary over one year is diluted in the representative volume of water defined by regulation.

Supporting Reports:

- *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036])
- *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]).

6.2.24 Diffusion in the SZ (2.2.07.17.0A)

FEP Description: Molecular diffusion processes may affect radionuclide transport in the SZ.

Screening Decision: Included

Screening Argument: N/A

TSPA Disposition:

This FEP addresses diffusive transport (e.g., fracture diffusion) such as is modeled numerically as part of the hydrodynamic dispersion coefficient (part mechanical dispersion, part diffusion). The effects of diffusion are particularly noticeable in a dual continuum media, such as that in effect in the Yucca Mountain volcanic units, where the majority of flow takes place in a limited number of fractures and minimal flow takes place in the rock matrix. Diffusion into the matrix occurs from a subset of all fractures in the fractured volcanic units (i.e., flowing intervals), as described in *Probability Distribution for Flowing Interval Spacing* (BSC 2004 [DIRS 170014]). Because the alluvium is not a dual continuum media, the effects of diffusion are minimal there. Data is available only from single-hole tracer tests conducted at the Alluvial Testing Complex (BSC 2004 [DIRS 170010], Section 6.5.4, Figures 6.5-18 through 6.5-20). Based on this available data, as a conservative approach no credit is taken for matrix diffusion into low-permeability regions within the alluvium. Thus, no credit is taken for diffusive transport in the alluvium.

In the site-scale transport model diffusion is one of two components of a dispersion tensor. This tensor, denoted as D' (BSC 2004 [DIRS 170036], Section 6.4.2.1), is the sum of the mechanical dispersion tensor (D) for the flow system and the coefficient of molecular diffusion (D_0) in porous media. Together, these processes are modeled using the stochastically sampled LDISP (BSC 2005 [DIRS 174012], Sections 6.7.2 and 6.5.2.9) and the transverse hydrodynamic dispersion parameter, which is a function of LDISP. The effects of molecular diffusion are explicitly included also in the displacement matrix given by Equation 55 in *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036], Section 6.4.2.3). The effects of molecular diffusion are, thus, explicitly included in the SZ transport model. These effects are significant only at low flow velocities (Bear 1972 [DIRS 156269], p. 581). The specific discharge value of 0.67 m/year reported in the *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036], Table 4-2) leads to fluid velocities on the order of 10^{-7} to 10^{-4} m/s. Combining this with the lower limit of the LDISP of 0.1 m given in Table 4-2 of *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036]), this leads to a lower limit of dispersion coefficient in excess of 10^{-8} m^2/s. The upper limit of effective diffusion coefficient for volcanic units given in Table 4-2 (BSC 2004 [DIRS 170036]) is 5×10^{-10} m^2/s. Thus, the effects of molecular diffusion, which are included in the SZ flow and transport models (BSC 2005 [DIRS 174012] Section 6.5.2.6) are overshadowed by advection and dispersion.

Colloid transport, as described in *Saturated Zone Colloid Transport* (BSC 2004 [DIRS 170006]), is also subject to diffusion but is also dominated by advection and hydrodynamic dispersion. Matrix diffusion (which contributes to retardation) is addressed in the FEP 2.2.08.08.0A–Matrix diffusion in the SZ.

Supporting Reports:

- *Saturated Zone Colloid Transport* (BSC 2004 [DIRS 170006])

- *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036])
- *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012])
- *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010])
- *Probability Distribution for Flowing Interval Spacing* (BSC 2004 [DIRS 170014]).

6.2.25 Chemical Characteristics of Groundwater in the SZ (2.2.08.01.0A)

FEP Description: Chemistry and other characteristics of groundwater in the saturated zone may affect groundwater flow and radionuclide transport of dissolved and colloidal species. Groundwater chemistry and other characteristics, including temperature, pH, Eh, ionic strength, and major ionic concentrations, may vary spatially throughout the system as a result of different rock mineralogy.

Screening Decision: Included

Screening Argument: N/A

TSPA Disposition:

Variations in temperature, pH, Eh, ionic strength, and major ionic concentrations in the groundwater affect sorption of radionuclides onto the rock surface and colloids, which, in turn, affect the sorption coefficient, K_d, and thus, the retardation factor, R_f, for each radionuclide. In the *Site-Scale Saturated Zone Transport* model (BSC 2004 [DIRS 170036], Appendices A and C), these coefficients are entered directly in the transport base-case model that describes radionuclide transport via the distribution coefficients and the retardation factors (BSC 2004 [DIRS 170036], Section 6.4.2.4.1, Equations 56 (a, b) and 57), which describe reactive transport through porous media. Appropriate ranges and distributions of values for K_ds (BSC 2004 [DIRS 170036], Appendix A) are chosen based on expert elicitation (CRWMS M&O 1998 [DIRS 100353], Section 3.2), and laboratory and field studies for the sorption coefficient K_d (BSC 2004 [DIRS 170036], Appendix A). These ranges implicitly include variations in the chemical characteristics of SZ waters. Of particular interest, partitioning coefficients are bounded by the assumption that SZ groundwaters are oxidizing (BSC 2004 [DIRS 170036], Section 6.3, Items 4 and 7). Geochemically significant variations in redox conditions have been observed in the saturated zone near Yucca Mountain (BSC 2004 [DIRS 170036], Appendix F Section F3). Reducing conditions are evident directly east of Yucca Mountain in wells H-3, H-4, WT-17, b#1, WT-10, WT-12 and WT-14, suggesting the existence of a north-south zone of reducing groundwaters in the volcanic units (BSC 2005 [DIRS 174958] Figure 2.1-2). This zone cuts across the transport pathways from the repository predicted by the flow model. Water chemistry in these wells to the south and east of Yucca Mountain, is consistent with reducing conditions associated with pyrite in the fractured tuff aquifer of the SZ (BSC 2005 [DIRS 174958] Section 2.1.3). Similar reducing conditions in groundwater have been observed in groundwater flow systems due to disseminated pyrite near a uranium mine in Japan (Iwatsuki and Yoshida 1999 [DIRS 172727]) and in fractured metasedimentary bedrock in Australia (Jankowski 2001 [DIRS 172771]).

Sorption coefficient distributions have been developed in the SZ transport AMR (BSC 2004 [DIRS 170036], Appendix A) assuming oxidizing redox conditions along potential flowpaths to the accessible environment, which biases the sorption coefficient distributions downward. The sorption coefficient parameter ranges are incorporated in the model abstraction through the K_d variables KDNPVO (neptunium sorption coefficient in volcanic units), KDRAVO (radium sorption coefficient in volcanic units), KDSRVO (strontium sorption coefficient in volcanic units), KDUVO (uranium sorption coefficient in volcanic units), KDNPAL (neptunium sorption coefficient in the alluvium), KDRAAL (radium sorption coefficient in the alluvium), KDSRAL (strontium sorption coefficient in the alluvium), KDUAL (uranium sorption coefficient in the alluvium), KD_AM_VO (americium sorption coefficient in the volcanic units), KD_CS_VO (cesium sorption coefficient in the volcanic units), KD_PU_VO (plutonium sorption coefficient in the volcanic units), KD_AM_AL (americium sorption coefficient in the alluvium), KD_CS_AL (cesium sorption coefficient in the alluvium), KD_PU_AL (plutonium sorption coefficient in the alluvium), and the equilibrium sorption between aqueous and solid phases and a colloidal phase containing sorbed radionuclides americium, cesium, protactinium, plutonium, and thorium (BSC 2005 [DIRS 174012], Section 6.5.2.8, Table 6-8). The sampled parameters Kd_Pu_Col and Kd_Cs_Col model partitioning between the aqueous and colloidal phases for plutonium and cesium, respectively (BSC 2005 [DIRS 174012], Section 6.5.2.12). The colloid retardation factor in the alluvium and the volcanic units are modeled through the sampled parameters, the colloid retardation factor in the alluvium (CORAL), and CORVO (the colloid retardation factor in volcanic units) (BSC 2005 [DIRS 174012], Section 6.5.2.11).

Regarding the spatial and temporal dependencies of K_d, geochemical analysis indicates that current SZ groundwater under the repository and along the SZ transport path is predominately oxidized paleoclimate recharge water (BSC 2004 [DIRS 170037], Appendix A, Section A7.1.2 consisting of predominantly oxidizing waters with a swath of reducing conditions directly east of Yucca Mountain in wells H-3, H-4, WT-17, b#1, WT-10, WT-12 and WT-14 (BSC 2005 [DIRS 174958] Figure 2.1-2). This suggests the existence of a north-south zone of reducing groundwaters in the volcanic units (BSC 2005 [DIRS 174958], Section 3). Spatial variability in the composition of the groundwater reflects, in part, temporal variability in recharge when data from the Fortymile Wash are included. Uncorrected groundwater ages determined from carbon-14 (percent modern carbon) data (DTN: MO0012MAJIONIS.000 [DIRS 153679], Table S00453_001) and an exponential decay relationship (BSC 2004 [DIRS 170037] equation A6-3) range from about 10,000 to 16,000 years old in the vicinity of Yucca Mountain. Using the reasonable approach that spatial variability within the recharge domain brackets the temporal variability expected to occur at a given location within the domain, the observed variability in geochemistry between wells J-13 and UE-25p#1 in the model area brackets the temporal variations expected to occur in the water composition (BSC 2004 [DIRS 170036], Appendix A, Section A3). Additionally, approximately a 100 m rise in the water table within the repository vicinity is taken as a reasonable upper bound for UZ transport simulations under glacial-transition climatic conditions (BSC 2004 [DIRS 170037], Section 6.4.5.2.1), corresponding to paleoclimatic conditions. Thus, the water quality of sampled paleoclimate recharge water reflects past interactions with rock types overlying the current water table as well as the rock types along the expected transport pathways. Consequently, the ranges in each radionuclide K_d and effective colloidal retardation factor bracket the temporal variations in water composition given volume and time of recharge, as well as the variability in pH, Eh, mineralogy, and the number of rock sorption sites.

Supporting Reports:

- *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037], Appendix)
- *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036])
- *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]).

6.2.26 Geochemical Interactions and Evolution in the SZ (2.2.08.03.0A)

FEP Description: Groundwater chemistry and other characteristics, including temperature, pH, Eh, ionic strength, and major ionic concentrations, may change through time, as a result of the evolution of the disposal system or from mixing with other waters. Geochemical interactions may lead to dissolution and precipitation of minerals along the groundwater flow path, affecting groundwater flow, rock properties, and sorption of radionuclides. Effects on hydrologic flow properties of the rock, radionuclide solubilities, sorption processes, and colloidal transport are relevant. Kinetics of chemical reactions should be considered in the context of the time scale of concern.

Screening Decision: Excluded–Low consequence

Screening Argument:

Geochemical analysis indicates current SZ groundwater under the repository and along the SZ transport path is paleoclimate recharge water (BSC 2004 [DIRS 170037], Appendix A, Section A7.1.2). These waters represent a mixture of waters from past flow systems having different climatic signatures than those indicative of current dry climatic conditions. Uncorrected SZ groundwater ages determined from carbon-14 (percent modern carbon) data (DTN: MO0012MAJIONIS.000 [DIRS 153679], Table S00453_001)) and an exponential decay relationship (BSC 2004 [DIRS 170037] equation A6-3) range from about 10,000 to 16,000 years old. Corrections to the groundwater age to account for geochemical interactions are small (BSC 2004 [DIRS 170037] Table A6-7), thus these waters are reflective of cooler climatic conditions and cooler recharge waters. Cooler water is able to dissolve more oxygen and thus has a higher oxidation state than warmer water (i.e., the temperature dependency of Henry's Law). Compared to recharge waters reflective of current climatic conditions, paleoclimate recharge waters have higher carbon contents and higher concentrations of dissolved CO_2, which contributes to a lower pH. Lower pHs and higher CO_2 concentrations equate to waters that are more aggressive and will participate in more dissolution and subsequent precipitation along the transport path compared to groundwaters originating from current climatic conditions. The ranges in radionuclide sorption coefficients (K_d) and effective colloidal retardation factors were derived based on variations in water chemistry, radionuclide concentrations, and variations in rock surface properties (BSC 2004 [DIRS 170036], Appendix A, Section A3 and BSC 2004 [DIRS 170006], Section 1). The temporal variations in water chemistry are small compared to the variations in current geochemical conditions. Therefore, temporal changes in water geochemistry are excluded based on low consequence. Specific details pertaining to variability in Eh are discussed below.

Regional Yucca Mountain SZ recharge waters mainly occur through direct infiltration through the UZ and not through surface water recharge (such as lakes and perennial rivers). Consequently, temporal changes in surface water quantities are excluded based on low consequence. Since hydrothermal activity is considered to be low consequence to regional SZ flow and flow paths in the Yucca Mountain vicinity (see FEP 1.2.06.00.0A–Hydrothermal activity), temporal geochemical changes due to an increase in geothermal (hydrothermal) activity will not affect SZ geochemistry and are therefore excluded based on low consequence.

For the TSPA-LA transport model (BSC 2004 [DIRS 170036], Section 6.3 and Appendix F), it is assumed that the groundwaters along the transport path are oxidizing from the UZ/SZ water table interface to the 18-km compliance boundary. However, there is evidence of localized reducing zones along the SZ transport pathway east of Yucca Mountain, that may result in the reduction of redox-sensitive radionuclides such as Tc (BSC 2005 [DIRS 174958], Section 2.1.3). These radionuclides are less soluble at lower oxidation states (i.e., reducing environments) and could precipitate out of solution and accumulate in localized reduction zones. A subsequent return to oxidizing conditions within the localized reduction zones during 10,000 years after closure would favor dissolution of these precipitates back into solution, causing groundwater concentrations to increase to levels above those that were in effect prior to reaching these reduction zones.

It is not likely the local reduction zones will be oxidized during the 10,000 years after closure, or will they increase in size. A large-scale change in oxidation state from that measured currently at Yucca Mountain is excluded on low consequence grounds. The rationale for this statement is as follows:

1. Reducing conditions found in Boreholes USW H-1, USW H-4, and UE-25b#1 (Ogard and Kerrisk 1984 [DIRS 100783], Section IV) and USW WT-17 (BSC 2004 [DIRS 170036], Appendix F, Section F2.2) argue that reducing conditions along this trend extend from the shallow saturated zone to the lower Tram Tuff (BSC 2005 [DIRS 174958] Section 2.1.2.1). The reducing agents for groundwater in these wells could be located in the groundwater itself or in the rock matrix. Because the reducing zones are local in extent, the aquifer matrix most likely supplies most of the reduction capacity. Generally, in volcanic rocks the reduction capacity is associated with solid sulfides (e.g., pyrite), biotite, and other ferrous iron-bearing minerals. Pyrite has been identified as a primary mineral component of the lower Tram Tuff (Castor et al. 1994 [DIRS 102495]) and believed to have been entrained in the ash-flow eruptions that produced the Tram Tuff (BSC 2005 [DIRS 174958] Section 2.1.2.1). Within the Yucca Mountain vicinity the Tram Tuff spans west of Bare Mountain, eastward to Jackass Flats, and southward to within five miles of Highway 95 (Carr et al. 1984 [DIRS 101522], Figure 11). Given that pyrite is a primary mineral component of the Tram Tuff within the Yucca Mountain vicinity, it promotes reducing conditions to exist in groundwater that come into contact with that unit (BSC 2005 [DIRS 174958] Section 2.1.2.1). Given the age, areal extent and mineral content of these volcanic

hydrogeologic units, it is inferred there is sufficient pyrite in these hydrogeologic units such that reducing conditions will be limited to its present day location and persist for 10,000 years after closure.

2. Resident groundwaters along the projected groundwater flow path are reflective of cooler climatic conditions and cooler recharge waters 10,000–16,000 years old (BSC 2004 [DIRS 170037], Appendix A, Section A6.3.6.6.2). Cooler water is able to dissolve more oxygen and thus has a higher oxidation state than warmer water (i.e., the temperature dependency of Henry's Law). Compared to recharge waters reflective of current climatic conditions, paleoclimate recharge waters have higher carbon contents and higher CO_2 concentrations, which also contributes to higher oxidation states and a lower pH. The above conditions promote more dissolution then that of groundwaters originating from current climatic conditions. As a result of higher solubility limits from these recharge waters subsequent precipitate in reducing zones will also increase. Consequently, the capability of future groundwaters, reflective of the current climate pulse, to further oxidize localized reducing zones within the next 10,000 years after closure is not credible.

3. There is no current mechanism known to support that reducing conditions will be more extensive along the flow path than what is currently measured. The total reduction capacities in the parent rock are a function of the concentration of the rock's in situ reducing agents and the volume of these reducing zones. To date, only localized reducing zones have been produced over the past several million years. It is reasonable to presume that this reduction capacity will remain localized over the relatively short 10,000 years after closure. Therefore, a significant increase in the size of these local reducing zones is not credible.

4. The occurrence of localized reducing conditions east of Yucca Mountain is likely controlled by the presence of pyrite in the tuff aquifer. An increase in recharge due to climate changes will not significantly overwhelm the variability in the existing redox conditions that have persisted for millions of years and not be depleted over the 10,000 years after closure. Therefore, an evolution from reducing to oxidizing conditions in current and local reducing zones is not likely to occur within 10,000 years after closure.

Detailed discussions pertaining to related FEPs in groundwater chemistry as they affect transport and sorption are addressed by FEPs 2.2.08.01.0A–Chemical characteristics of groundwater in the SZ, 2.2.08.06.0A–Complexation in the SZ; 2.2.08.07.0A–Radionuclide solubility limits in the SZ; 2.2.08.09.0A–Sorption in SZ; 2.2.08.10.0A–Colloid transport in the SZ; and the following analysis and model reports: *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037], Appendix A, Section A-6.7); *Saturated Zone Colloid Transport* (BSC 2004 [DIRS 170006]); and *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036], Appendices A, B, C, and D). All of the above reasoned arguments support the conclusion that geochemical interactions and evolution is excluded based on low consequence to radiation exposure to the RMEI.

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.27 Complexation in the SZ (2.2.08.06.0A)

FEP Description: Complexing agents such as humic and fulvic acids present in natural groundwaters could affect radionuclide transport in the SZ.

Screening Decision: Included

Screening Argument: N/A

TSPA Disposition:

Complexing agents are included in the TSPA-LA (BSC 2004 [DIRS 170036], Appendix A7.3). The surface-complexation models include the effects of competition from common constituents in the rock such as calcium, magnesium, sodium, potassium, and aluminum. In the SZ inorganic complexing agents, such as carbonates, are dominant, whereas organic complexing agents are not found in significant amounts (see FEP 2.2.09.01.0A – Microbial activity in the SZ). Complexing agents can affect sorption of radionuclides onto the rock surface and colloids. The sorption coefficients K_d (radionuclide sorption coefficients on the rock surfaces) and K_c (radionuclide sorption coefficients on colloids) enter via Equations 56 (a), 56 (b), 57, 76, 77, and 78 in *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036], Sections 6.4.2.4.1), which describe reactive transport through porous media. These effects are included in the model by choosing appropriate ranges of values for the sorption coefficients K_d and K_c as described in *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036], Appendices A and B, respectively) and incorporated in the *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012], Sections 6.5.2.8, 6.5.2.11 and 6.5.2.12 and Table 6-8). Available data are summarized in *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036], Appendices A, C and D). The parameter distributions for K_d and K_c are developed on the basis of these data.

Supporting Reports:

- *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036])
- *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]).

6.2.28 Radionuclide Solubility Limits in the SZ (2.2.08.07.0A)

FEP Description: Solubility limits for radionuclides may be different in saturated zone groundwater than in the water in the unsaturated zone or in the waste and EBS.

Screening Decision: Excluded–Low consequence

Screening Argument:

The *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]) does not implement a solubility limit for each transported radionuclide (similar to the UZ and the EBS regions). Solubility limits are imposed at the source term in the TSPA (BSC 2005 [DIRS 174566], Section 8.1). This implementation allows the radionuclide solution concentration that is introduced into SZ from the UZ to be unconstrained. The rationale supporting this position is as follows. Solubility determines the maximum concentration a constituent can reach in the aqueous phase solution; therefore it is considered a bounding property. Once a particular radionuclide reaches that maximum concentration or solubility limit, it will form a precipitate or solid. The solid can be either a pure radionuclide-bearing solid or a solid solution of two (or more) end members. The radionuclide constituent will then be in equilibrium between the solid and aqueous phase. The precipitate-forming solid phase will increase in mass until the concentration in the solution phase falls below the solubility limit. Once this happens, the solid phase will then "dissolve" into the aqueous phase.

Along the SZ transport path in-situ waters are primarily oxidizing, and modeled as such in the TSPA. Radionuclide constituents introduced in the SZ from the UZ are more soluble in oxidizing waters than reducing waters. However, situated in the volcanic units (primarily the Tram Tuff), southeast of the repository footprint and within the first quarter of the predicted SZ path, there exists a reducing zone (BSC 2005 [DIRS 174958], Figure 2.1-2). This zone cuts across the transport pathways from the repository predicted by the flow model. If a solution containing a redox-sensitive constituent passes through this reducing region, that constituent will precipitate out of solution, resulting in lower solution concentrations.

The effects of such a process is investigated in a sensitivity study reported in (BSC 2005 [DIRS 174958]). Here, the redox-sensitive radionuclide Tc is introduced in oxidizing SZ waters, then transported through a thin reducing zone within the first quarter section of the path length (BSC 2005 [DIRS 174958], Figure 2.6-1). As expected, when the radionuclide concentrations pass through the thin reducing zone, Tc solubility is exceeded and Tc precipitates form, thus lowering Tc solution concentrations. The Tc solution concentrations remain at these lower levels downstream and well beyond the 'exit point' of the reducing zone. Furthermore, the existence of the thin reducing zone produces a significant delay in Tc peak concentrations at the compliance boundary (BSC 2005 [DIRS 174958], Section 3). The study concludes that implementing solubility limits in the SZ, due to the presences of a 'thin curtain' of reducing conditions that lie along the SZ transport path, would reduce concentration levels of redox-sensitive constituents and significantly increase transport times. (BSC 2005 [DIRS 174958], Section 3)

The sensitivity study supports the supposition that if a solubility limit were to be imposed into the SZ model that is lower than that implemented in the *Dissolved Concentration Limits of Radioactive Elements* (BSC 2005 [DIRS 174566]), it would cause precipitates to form, pulling constituents out of the aqueous phase and reducing the maximum aqueous concentration capable of being transported downstream to the compliance boundary.

Potential precipitation of a radionuclide due to solubility limits in the SZ would increase the transport time of that radionuclide in the SZ relative to the approach assuming no precipitation. Additionally, physical build-up of a solid phase onto mineral surfaces (due to precipitation, not adsorption) can reduce permeability, increase tortuosity, and clog pores, thus increasing transport times. Longer transport times in the SZ allow radioactive decay to diminish the mass of radionuclides that are ultimately released to the accessible environment. Consequently, the process of precipitation due to solubility limits would enhance the performance of the SZ with regard to its capability as a barrier to radionuclide migration.

In summary, introduction of a solubility limit in the SZ would be beneficial to performance. Therefore, this FEP is excluded based on low consequence because not imposing a solubility limit in the model has no adverse effects on performance.

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.29 Matrix Diffusion in the SZ (2.2.08.08.0A)

FEP Description: Matrix diffusion is the process by which radionuclides and other species transported in the SZ by advective flow in fractures or other pathways move into the matrix of the porous rock by diffusion. Matrix diffusion can be a very efficient retarding mechanism, especially for strongly sorbed radionuclides, due to the increase in rock surface accessible to sorption.

Screening Decision: Included

Screening Argument: N/A

TSPA Disposition:

Matrix diffusion is the process by which radionuclides transported in the SZ move into the matrix of the porous rock. This process can be a very effective retarding mechanism and is explicitly included in the conceptual model of transport in the mathematical model transport Equations 56 and 57, Section 6.4.2.4.1 of *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036]), and in the numerical implementation of the model FEHM through the use of the diffusion coefficient and the random-walk particle-tracking method with a semi-analytical solution. Colloids undergo retardation in fractured volcanic rocks (BSC 2004 [DIRS 170006]) but are not subject to matrix diffusion in the simulations of colloid-facilitated radionuclide transport (BSC 2004 [DIRS 170036], Section 6.4.2.6). Diffusion into the matrix occurs from a subset of all fractures in the fractured volcanic units (i.e., flowing intervals), as described in *Probability Distribution for Flowing Interval Spacing* (BSC 2004 [DIRS 170014]).

Matrix diffusion is included in the SZ transport model abstraction (BSC 2005 [DIRS 174012], Section 6.3.1 and Table 6-8) through the matrix diffusion parameter diffusion coefficient in volcanic units (DCVO), and is sensitive to the volcanic matrix permeability and volcanic matrix porosity (BSC 2005 [DIRS 174012], Section 6.5.2.6). The semianalytical matrix diffusion equation obeys Fick's law and incorporates concentration gradients and the temporal and spatial changes in the gradient along the transport pathway. Matrix diffusion is modeled only in the matrix portion of the volcanic units (BSC 2005 [DIRS 174012], Section 6.5.2.6). The cumulative distribution function for the DVCO is based on:

- Field and laboratory diffusion experiments performed in and on volcanic tuffs located within the Yucca Mountain vicinity (BSC 2005, [DIRS 174012], Section 6.5.2.6)
- A least-squares linear empirical equation fit to diffusion experiment results and measured values for matrix porosity and permeability (Reimus et al. 2002 [DIRS 163008], p. 2.25)

The effective matrix diffusion coefficients for diffusing radionuclides are stochastically sampled from this same cumulative distribution function.

Given the inhomogeneous nature of the alluvium, flow could preferentially occur through high permeability regions, and matrix diffusion could potentially occur into the low permeability regions of the alluvium. Data is available only from single-hole tracer tests conducted at the Alluvial Testing Complex (BSC 2004 [DIRS 170010], Section 6.5.4, Figures 6.5-18 through 6.5-20). Based on this available data, as a conservative approach no credit is taken for matrix diffusion into low-permeability regions within the alluvium. Similarly, no credit is taken for matrix diffusion of colloids in either the volcanic units or the alluvium, because the effects would be small and would only retard transport.

Supporting Reports:

- *Probability Distribution for Flowing Interval Spacing* (BSC 2004 [DIRS 170014])
- *Saturated Zone Colloid Transport* (BSC 2004 [DIRS 170006])
- *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036])
- *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012])
- *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010]).

6.2.30 Sorption in the SZ (2.2.08.09.0A)

FEP Description: Sorption of dissolved and colloidal radionuclides in the SZ can occur on the surfaces of both fractures and matrix in rock or soil along the transport path. Sorption may be reversible or irreversible, and it may occur as a linear or nonlinear process. Sorption kinetics and the availability of sites for sorption should be considered. Sorption is a function of the radioelement type, mineral type, and groundwater composition.

Screening Decision: Included

Screening Argument: N/A

TSPA Disposition:

Sorption of radionuclides onto rock surfaces can occur both in the volcanic rocks and the alluvium (BSC 2004 [DIRS 170036], Appendix A). This process is modeled through a suite of partitioning coefficients, K_ds (BSC 2005 [DIRS 174012], Section 6.5.2.8) for the radionuclides americium, cesium, neptunium, protactinium, plutonium, radium, strontium, thorium, and uranium (BSC 2004 [DIRS 170036], Section 6.3 (Item 4 and 7), 6.4.2.4, 6.4.2.5 and Appendix A, Sections A7 and A.8). The process of sorption during transport in fractured volcanic units has been confirmed at the field scale by tracer testing at the C-wells complex (BSC 2004 [DIRS 170010], Section 6.3).

For many radionuclides the sorption kinetic time frame is relatively slow compared to the solute flow rates adjacent to the sorbing sites. That is, the exposure times of solute passing the sorbing sites is fast relative to the time it takes for the dissolved mass to sorb to the potential sorption sites. Additionally, the affinity of solute to sorb to a solid (the sorbing site) is dependent on the mineral composition and the shape of the solid. In the SZ flow and transport domain, the uncertainty in sorption kinetics is implemented by biasing sorption kinetics downward. Effectively, the model adopts partitioning coefficients based on the low points of the laboratory-derived sorption isotherms. This approach underestimates the range, median, and mean partitioning coefficient values used for the nine radionuclide classes modeled in the SZ (BSC 2004 [DIRS 170036], Appendices A and D).

In the volcanic rocks, sorption in the matrix is explicitly included in the retardation coefficient R_f in Equations 56b and 57 of *Site-Scale Saturated Zone Transport*, (BSC 2004 [DIRS 170036], Section 6.4.2.5). Sorption within individual fractures is not included in the conceptual model; however, sorption can occur within flowing zones due to the rubblized matrix. This effect is included in the retardation coefficient R in Equation 56a in Section 6.4.2.4.1 of the site-scale SZ transport report; sorption in the alluvium is described in Equation 77 (BSC 2004 [DIRS 170036], Section 6.4.2.4.1).

Sorption coefficients for some radionuclides, specifically Np and Tc, exhibit sensitivity to redox conditions of groundwater, with significantly greater sorption under more reducing conditions (Langmuir 1997 [DIRS 100051]). Reducing conditions are evident directly east of Yucca Mountain in wells H-3, H-4, WT-17, b#1, WT-10, WT-12 and WT-14, suggesting the existence of a north-south zone of reducing groundwaters in the volcanic units (BSC 2005 [DIRS 174958], Figure 2.1-2). The inclusion of even a 'narrow reducing zone' in the SZ transport simulations results in greater overall retardation of Np and Tc, furthering delaying their release (BSC 2005 [DIRS 174958], Table 2.6-2). Sorption coefficient distributions have been developed in the SZ transport AMR (BSC 2004 [DIRS 170036], Section 6.3 and Appendix F) assuming redox conditions were oxidizing along potential flowpaths to the accessible environment which biases the sorption coefficient distributions for Np and Tc downward. Radionuclides modeled as entrained "irreversible" colloids in *Waste Form and In-Drift Colloids-Associated Radionuclide Concentrations: Abstraction and Summary* (BSC 2005 [DIRS 174290], Section 6.3.1) are sorbed as well. The alluvium is largely composed of disaggregated tuffaceous material, mixed with clays and other secondary minerals. Each developed radionuclide K_d distribution brackets the regional variability in K_d values due to variations in pH, Eh, water composition (representative of J-13 and UE-25 p#1 waters), mineralogy, and the number of rock sorption sites. Additionally, K_d distributions encompass the potential nonlinear behavior of the sorption processes, thus accounting for sorption kinetics (BSC 2004 [DIRS 170036], Table 6.6-1b, Appendix A, Section A7).

The volcanic units are primarily composed of zeolitic and devitrified tuffaceous materials. The alluvium is largely composed of disaggregated tuffaceous material, mixed with clays and other secondary minerals. Because radionuclides have a greater sorption affinity onto clays and secondary minerals than tuffaceous materials, alluvium K_d values are slightly higher than those for the volcanic units (BSC 2004 [DIRS 170036], Appendix A, Section A7.4.3) and are reflected as such in alluvium K_d distributions. Table A-4 in *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036]) summarizes SZ sorption model parameters.

<u>Sorption of Dissolved Radionuclides:</u> In the volcanic units, Np, Ra, strontium, and uranium sorption between the aqueous phase and the solid phase (parent rock) is modeled in the FEHM flow and transport code using the sampled parameters KDNPVO, KDRAVO, KDSRVO, KDUVO, respectively (BSC 2005 [DIRS 174012], Section 6.5.2.8 and Table 6-8); sorption for the same radionuclides in the alluvium is modeled through the parameters KDNPAL, KDRAAL, KDSRAL, and KDUAL (BSC 2005 [DIRS 174012], Section 6.5.2.8 and Table 6-8).

<u>Sorption of Reversible Colloids:</u> Equilibrium sorption between aqueous and solid phases and a colloidal phase is modeled for nine radionuclide classes represented by partitioning of the radionuclides americium, cesium, protactinium, plutonium, and thorium (BSC 2004 [DIRS 170036], Section 6.4.2.6 and Table 5-1). The sampled parameters Kd_Pu_Col and Kd_Cs_Col model partitioning of plutonium and cesium between the aqueous and colloidal phases, respectively. Partitioning between the aqueous and colloidal phase for the radionuclides americium, thorium, and protactinium is modeled through the sampled parameter Kd_Am_Col (BSC 2005 [DIRS 174012], Section 6.5.2.12). Partitioning between the colloidal and aqueous phase is the same in both the volcanic units and the alluvium. Partitioning between the aqueous and solid phase (parent rock) for each species differs between the volcanic and alluvial units. In the volcanic units, plutonium and cesium aqueous- and solid-phase partitioning is modeled through the sampled parameters Kd_Pu_Vo and Kd_Cs_Vo, respectively. For americium, thorium, and protactinium, the same partitioning is modeled through the single sampled parameter Kd_Am_Vo. In the alluvium, plutonium and cesium partitioning between aqueous and solid phases is modeled with the sampled parameters Kd_Pu_Al, Kd_Cs_Al; for americium, protactinium, and thorium, it is modeled through the parameter Kd_Am_Al.

<u>Sorption of Irreversible Colloids:</u> In the volcanic units, the dispersed "advectively" transported plutonium and americium colloids (BSC 2004 [DIRS 170006], Section 6.4 and BSC 2005 [DIRS 174290], Section 6.3.3.2) sorb onto fracture surfaces through a colloid retardation factor CORVO (BSC 2005 [DIRS 174012], Section 6.5.2.11). In the alluvium, these same colloids are effectively sorbed via a sampled retardation factor CORAL (BSC 2005 [DIRS 174012], Section 6.5.2.11).

Table 6.2-2 summarizes which radionuclides have sorption coefficients (Kd) assigned to them, their parameter name, whether they are sorbed reversibly or irreversibly to the parent rock, colloids, or both (i.e., in secular equilibrium with which surface components).

Table 6.2-2.Summary of the SZ Sampled Parameters Specific to Radionuclide Sorption

Radionuclide Partitioned Between Solution and Parent Rock (No colloid transport)			Radionuclide Partitioning Parameters Between Colloids and Parent Rock			Radionuclide Irreversibly Sorbed to Colloids	
			Sorption Between Solution and Rock Surface		Sorption Between Solution and colloids		
RN	**Volcanic Units**	**Alluvium**	**Volcanic Units**	**Alluvium**		**Volcanic Units**	**Alluvium**
Am	No	No	Yes KD_Am_VO	Yes KD_Am_AL	Yes KD_Am_Col	Yes CORVO	Yes CORAL
Cs	No	No	Yes KD_Cs_VO	Yes KD_Cs_AL	Yes KD_Cs_Col	No	No
Np	Yes KDNPVO	Yes KDNPAL	No	No	No	No	No
Pa	No	No	Yes KD_Am_VO	Yes KD_Am_AL	Yes KD_Am_Col	No	No
Pu	No	No	Yes KD_Pu_VO	Yes KD_Pu_AL	Yes KD_Pu_Col	Yes CORVO	Yes CORAL
Ra	Yes KDRAVO	Yes KDRAAL	No	No	No	No	No
Sr	Yes KDSRVO	Yes KDSRAL	No	No	No	No	No
Th	No	No	Yes KD_Am_VO	Yes KD_Am_AL	Yes KD_Am_Col	No	No
U	Yes KDUVO	Yes KDUAL	No	No	No	No	No

Source: BSC 2005 [DIRS 174012], Sections 6.5.2.8, 6.5.2.11, 6.5.2.12.

RN = radionuclide

Supporting Reports:

- *Saturated Zone Colloid Transport* (BSC 2004 [DIRS 170006])
- *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036])
- *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012])
- *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010]).

6.2.31 Colloidal Transport in the SZ (2.2.08.10.0A)

FEP Description: Radionuclides may be transported in groundwater in the SZ as colloidal species. Types of colloids include true colloids, pseudo colloids, and microbial colloids.

Screening Decision: Included

Screening Argument: N/A

TSPA Disposition:

The colloid-facilitated transport of radionuclides is explicitly included in the SZ transport abstraction model and the SZ one-dimensional transport model (BSC 2005 [DIRS 174012] Sections 6.5.2.11 and 6.5.2.12). Colloids are subject to advection in the alluvium and fractures of tuff units and are not assumed to diffuse into the fractured rock matrix (BSC 2004 [DIRS 170036], Section 6.4.2.6 and Appendix B). Colloid transport in the SZ has been investigated at the field scale by tracer testing using microspheres, as described in *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010], Section 6.3). Radionuclide transport in association with colloids is simulated to occur by two modes: (1) as reversibly sorbed onto colloids, and (2) as irreversibly attached to colloids (BSC 2005 [DIRS 174012], Sections 6.5.2.11 and 6.5.2.12). Reversible sorption of radionuclides may occur onto any colloidal material present in the groundwater, and measurements of natural colloids in groundwater of the SZ include mineral and microbial colloids. Colloids with irreversibly attached radionuclides originate from the degradation of the glass waste form in the repository (BSC 2005 [DIRS 174290], Section 6.3.1). Colloids with irreversibly attached radionuclides are subject to retardation in the SZ both in the fractured tuff and the alluvium. However, a small fraction of colloids with irreversibly attached radionuclides are transported through the SZ with no retardation due to the kinetic nature of colloid attachment to the aquifer materials (BSC 2004 [DIRS 170006], Section 6.6) The parameter distributions related to reversible sorption onto colloids are based on field observations and laboratory experiments performed on colloids and geochemical conditions found in the Yucca Mountain vicinity (BSC 2004 [DIRS 170006], Section 7). These are labeled as Kd_Am_Col, Kd_Pu_Col, Kd_Cs_Col, and Conc_Col (groundwater concentration of colloids) in *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012], Table 6-8). The parameters related to the retardation of colloids with irreversibly attached radionuclides are CORVO and CORAL (BSC 2005 [DIRS 174012], Table 6-8).

Supporting Reports:

- *Saturated Zone Colloid Transport* (BSC 2004 [DIRS 170006])
- *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036])
- *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012])
- *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010]).

6.2.32 Groundwater Discharge to Surface Within the Reference Biosphere (2.2.08.11.0A)

FEP Description: Radionuclides transported in groundwater as solutes or solid materials (colloids) from the far-field may discharge at specific "entry" points that are within the reference biosphere. Natural surface discharge points, including those resulting from water table or capillary rise, may be surface water bodies (rivers, lakes), springs, wetlands, holding ponds, or unsaturated soils.

Screening Decision: Excluded–Low consequence

Screening Argument:

Currently, groundwater discharge from the Yucca Mountain flow system occurs at Franklin Lake Playa (also known as Alkali Flat) and Ash Meadows (D'Agnese et al. 1997 [DIRS 100131] pp. 40 to 48), both over 10 km beyond the 18-km accessible environment boundary (BSC 2004 [DIRS 170002], Figure 6-3). There is evidence of paleospring discharge points within northern Amargosa Desert that could become reactivated during wetter climatic conditions. These are the paleospring deposits located in Crater Flat, Crater Flat Wash, Amargosa Valley Diatomite, Indian Pass, Scranton Well, Mesquite Wash and the Amargosa River Snail Site (Paces et. al 1997 [DIRS 109148]). The Stranton Wells, Mesquite Wash and Amargosa River Snail Site paleospring deposits lie at the far terminus of Fortymile Wash and downstream from the projected flow path (from the repository to the 18-km boundary). The other paleospring deposits are separated from Fortymile Wash by faults and ridges and are not along the projected transport path. Therefore, they would not contain contaminants originating from the repository if reactivated under wetter climatic conditions.

Geochemical analysis indicates paleospring deposits along the far terminus of Fortymile Wash are not likely to be activated within the 10,000 years after closure. With the exception of the Amargosa River Snail Site, geochemical dating indicates the last episode of paleospring activity for the majority of paleosprings occurred between 14–20 ka ago (Paces et. al 1997 [DIRS 109148]). Scranton Wells was active 40–60 ka, Mesquite Wash active 30 ka, and the Amargosa River Snail Site between 9 to 12 ka (Paces et. al 1997 [DIRS 109148]). There is some uncertainty regarding the 9–12 ka activity for the Amargosa River Snail Site. Surface 'lag' samples taken from this site, and collected for dating, indicate plant petrifications may have tapped a subsided water source (a one-time discharge point that has been lowered below the ground surface). Thus surface discharge may have ceased much earlier than indicated from geochemical dating. Nevertheless, if the plume potentially discharges at those few reactivated discharge deposits located south of Fortymile Wash, it would be of a lower concentration than that at the 18-km boundary, simply because these locations are located several kilometers beyond the accessible environment boundary. Longer path lengths from the repository facilitate the processes of sorption and transverse dispersion; these two processes lower the plume's concentration levels as the path length increases. Additionally, a longer path length coupled with more sorption and dispersion equates to longer transport times, thus allowing more time for radioactive decay; more time for decay reduces the radionuclide concentrations in groundwater withdrawn from the community wells.

Groundwater modeling results demonstrate any discharge to the land surface within the next 10,000 years, if it occurs at all, would be expected to occur at least 4 km downstream of the 18-km boundary. D'Agnese et al.'s (1999 [DIRS 120425]) Death Valley regional groundwater model investigated future spring locations given a full glacial climate scenario and a postglacial warming scenario. Results from the full glacial simulations show groundwater discharging at the land surface in Fortymile Wash located about 4 km downstream from the 18-km boundary. Under the postglacial warming scenario, these simulations resulted in land surface discharge occurring about 8 km beyond the 18-km boundary. The full glacial climate scenario assumes the wettest climate conditions within the 400,000 year climate cycle. For 10,000 years after closure, climatic conditions will be in a glacial transition phase, which is not as wet or cool as the full glacial climate scenario. Therefore, predicted groundwater discharge using the full glacial climate scenario is considered unrealistic (too much recharge) within the 10,000 year time frame of interest (BSC 2004 [DIRS 170002], Section 6.3 and Figure 6.3).

Flow and transport modeling efforts were performed on the SZ site-scale model domain to assess water table elevations reflective of glacial climatic conditions (BSC 2004 [DIRS 170036], Appendix E). For these simulations the water table was allowed to rise under the repository by as much as 100 m. Model results from these simulations do not manifest spring formation within the 18-km boundary but do show a shallow water table within 5 m of the surface. The shallow water table corresponds to the three paleospring deposits located along Highway 95 and at the southern end of Crater Flat (BSC 2004 [DIRS 170037], Figure 6-12). All are located within the 'fork' of the Solitario Canyon Splay fault (BSC 2004 [DIRS 170037], Figure 6-37). Even if the water table were to rise another 5 m to form springs, the splay fault (BSC 2004 [DIRS 170037], Figure 6-37) serves as a barrier between Crater Flat and Fortymile Wash. It is in the Fortymile Wash where flow paths from the repository to the 18-km boundary converge. Consequently, if springs were to develop in the shallow water table area, radionuclides released from the repository will not likely be constituents of the spring waters.

In summary, current natural groundwater discharge points along the SZ flow paths are several kilometers downstream from the 18-km boundary. Future discharge points, if they occur at all, will be located several kilometers downstream from the 18-km boundary. Radionuclide concentrations at natural discharge locations would be less than concentrations at the 18-km boundary due to increased dispersion and sorption. Thus, future potential natural discharge points in the accessible environment will implicitly have a lower concentration than groundwater that crosses the 18-km boundary. Natural groundwater discharged to the surface several kilometers downstream from the reference biosphere will have more lateral dispersion, sorption, and a longer time for radioactive decay, thus a lower concentration than groundwater withdrawn from the community wells.

The biosphere model for the groundwater exposure scenario includes all exposure pathways expected to contribute to the annual dose to the RMEI, as required by 10 CFR 63.311 [DIRS 173273]. Exposure is calculated for the radionuclide concentration in groundwater at the boundary of the accessible environment. As noted above, this concentration would be greater than that for the predicted discharge points along the groundwater flow path from Yucca Mountain, downstream from the compliance point. The potential pathways from exposure to water flowing from reactivated springs or other groundwater discharge points are (1) consumption of water, (2) external exposure from contaminated soil around springs, and

(3) water immersion. These pathways are included in the biosphere model because groundwater entering the biosphere from a spring or other discharge point would be used in the same way as groundwater from a well. Moreover, the consequences of exposure arising from a spring would be negligible compared to the exposure received from the pathways included in the biosphere model. For example, consumption of water from a spring by the RMEI would not affect the calculated dose because exposure from drinking water is modeled using the radionuclide concentration at the compliance point and a fixed water consumption rate, as required by 10 CFR 63.312(c) [DIRS 173273]. External exposure from water was excluded from the biosphere model because immersion in water from a spring or well would have an insignificant contribution to the dose (BSC 2004 [DIRS 169460], Section 7.4.8.2). External exposure from the soil around springs would not exceed external exposure calculated in the biosphere model because the average exposure time at springs for the population would be low and the external exposure in that model is calculated for cultivated soil continuously irrigated with contaminated water. The concentration of radionuclides in irrigated soil would be higher than in soil around springs at the predicted discharge points along the groundwater flow path from Yucca Mountain.

In conclusion, it is not necessary to specifically address the potential consequences of exposure to water discharged to the surface within the reference biosphere because such exposure would be insignificant and is bounded by the dose calculated using the biosphere model. As a result, this FEP has no adverse effects on performance and is excluded based on low consequence.

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.33 Microbial Activity in the SZ (2.2.09.01.0A)

FEP Description: Microbial activity in the SZ may affect radionuclide mobility in rock and soil through colloidal processes, by influencing the availability of complexing agents, or by influencing groundwater chemistry.

Screening Decision: Excluded–Low consequence

Screening Argument:

Microbial activity can potentially change groundwater pH and Eh and introduce additional complexing agents, which could affect K_d distributions. Of interest is sorption behavior of a limited number of elements, particularly uranium and Np, which are affected by variations in water chemistry. In the SZ evidence of microbial activity is minimal, which is supported by geochemical analysis of groundwater samples taken from SZ wells within the Yucca Mountain vicinity (DTN: GS931100121347.007 [DIRS 149611], Table S96375 009); DTN: GS010308312322.003 [DIRS 154734], Table S01053 003). Results from this analysis found little to no organic carbon in these waters. Additionally, an autotrophic microbial reaction, if it occurs, will not generate CO_2, because it is a CO_2-fixation process, and the accumulated biomass will probably be recycled back to CO_2, resulting in zero CO_2 accumulation or depletion. Even if all the organic carbon were converted to carbon dioxide, the perturbation to the water chemistry is negligible. Therefore, the impact of microbial activity on water chemistry (pH and ΣCO_2) will be negligible (BSC 2004 [DIRS 169991], Section 7.1). It is logically concluded, because there is little organic carbon found in SZ waters, there is insignificant microbial activity in the SZ regime.

Uncorrected SZ groundwater ages determined from carbon-14 (percent modern carbon) data (DTN: MO0012MAJIONIS.000 [DIRS 153679], Table S00453_001)) and an exponential decay relationship (BSC 2004 [DIRS 170037] equation A6-3) range from about 10,000 to 16,000 years old. Corrections to the groundwater age to account for geochemical interactions are small (BSC 2004 [DIRS 170037] Table A6-7), thus SZ groundwaters are reflective of cooler climatic conditions and cooler recharge waters. Paleoclimate recharge waters have higher carbonate concentrations, which are components of inorganic complexing agents and higher concentrations of dissolved CO_2 gas (BSC 2004 [DIRS 170037], Appendix A, Sections A6.3.5.2, and A6.3.5.3). Higher CO_2 gas concentrations contribute to lower pH in resident waters, resulting in solutions that are more aggressive, participate in more dissolution and precipitation along the transport path, and the production of inorganic complexing agents. Two end-member groundwater compositions that could exist within the SZ, reflective of the large variability in paleoclimate recharge waters, were used in deriving the K_d distributions: water from wells UE-25p#1 and J-13 and *Site-Scale Saturated Zone Transport,* (BSC 2004 [DIRS 170036], Appendix A, Section A3). The resulting distributions used to represent the uncertainty in K_d and colloid parameter values, inclusive of uranium and plutonium, are based on conditions in the natural system dominated by the more aggressive nature of paleoclimate recharge waters and overshadow any effects naturally occurring microbial activity would have on SZ water chemistry.

Furthermore, radionuclide-bearing colloidal formation, transport, and complexation are dominated by natural inorganic ligands and inorganic constituents generated by the degradation of emplaced waste forms and not those produced by SZ microbes (BSC 2005 [DIRS 174290], Section 6.3.1). In conclusion, including the effects of microbial activity will not affect water chemistry used to derive K_d distribution and the presence of radionuclide-bearing colloids. This FEP is excluded based on low consequence because it will not significantly change radiation exposure to the RMEI or radionuclide releases to the accessible environment.

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.34 Thermal Convection Cell Develops in SZ (2.2.10.02.0A)

FEP Description: Thermal effects due to waste emplacement result in convective flow in the saturated zone beneath the repository.

Screening Decision: Excluded–Low consequence

Screening Argument:

To evaluate thermal effects in the SZ due to waste emplacement two mechanisms that could potentially induce convective flow of groundwater are examined. The first mechanism evaluates the potential for convective flow cells to occur as a result of increasing temperatures from the repository. The Rayleigh number is examined with respect to the decrease in the potential for thermally induced convection to occur. The second mechanism examines the potential for flow to occur due to mounding of the water table resulting from increased temperatures and decreased density of groundwater in the SZ below the repository. Groundwater flow in the SZ near the water table and outward from the mound could potentially impact the transport of radionclides in the SZ. The hydraulic gradient resulting from the mounding of the water table is compared to the natural flow gradient. Detailed discussion of these two mechanisms is provided below.

These effects would lead primarily to greater transverse mixing and dispersion in the SZ below the repository. In addition the migration rate of radionuclides in the groundwater could be increased in those areas where the convective outflow of groundwater would be additive to the ambient groundwater movement.

A three-dimensional heat conduction model of the repository is used to estimate the temperature at the water table and within the SZ, as a function of time following emplacement of the waste (see Appendix C of this report). The estimate for maximum temperature at the water table due to repository heating is about 60°C based upon an ambient temperature of 34°C. Although ambient groundwater flow will convect heat away from the area below the repository, it is assumed that the groundwater near the water table is stagnant and that none of the heat is swept downgradient by flow in the SZ. Consequently, the three-dimensional heat conduction model overestimates the values of temperature at and below the water table.

Development of thermal convection cells in porous media is classically driven by an underlying heat source. In the case of the SZ at Yucca Mountain the repository heat source is located above the SZ, in the UZ. Increased temperature in the SZ near the water table would decrease the potential for the development of classical thermally driven convection cells by decreasing the magnitude of the ambient geothermal gradient in the upper part of the SZ.

The theoretical potential for the initiation of thermal convection currents in a horizontal porous medium heated from below is given by the modified Rayleigh number N_{RA} (e.g. Domenico and Schwartz, 1990, [DIRS 100569] p. 344-345):

$$N_{RA} = \frac{g\rho_o(c_w\rho_w)Hk\alpha_f\Delta T}{\mu\kappa_e}$$

Where g is the acceleration of gravity, ρ_o is the reference density of water, c_w is the specific heat of water, ρ_w is the density of water, H is the aquifer thickness, k is the intrinsic permeability, α_f is the coefficient of thermal expansion of water, ΔT is the difference in temperature between the bottom and top of the aquifer, μ is the viscosity of water, and κ_e is the effective thermal conductivity. An increase in the temperature at the water table would decrease the value of the ΔT term in this expression, resulting in a smaller value for N_{RA} and a decrease in the potential for thermal convection via this mechanism.

Mounding of the water table may occur due to the repository serving as a heat source to the groundwater in the SZ. The local rise in the water table can create a potential for lateral flow at or near the water table, in addition to the ambient flow beneath the water table surface. The associated water table gradient will tend to increase the velocity of radionuclide transport in the SZ between the heated region beneath the repository, and the downgradient edge of the heated region, due to water table mounding. The analysis presented below estimates an upper bound on the mound height by considering a hydrostatic, or no flow condition. Groundwater flow away from the water table mound would tend to dissipate the heat from the repository, as well as any radionuclides released to the SZ, and result in a lowering of the mound.

Consider a saturated column of permeable rock with the top at the water table (z=0 m) and the bottom at a depth at which the temperature is relatively unchanged by the repository ($z=z_d=800$ m based on three-dimensional modeling results; see Appendix C this report). The pressure at the bottom of the column is given by:

$$p_w = \int_0^{z_d} \rho(z) g dz$$

Where $\rho(z)$ is the water density and g is the gravitational constant. Assuming a linear thermal gradient, and linear relationship between the temperature and density, this equation becomes:

$$p_w = z_d \left(\rho(0) + \rho(z_d)\right) g / 2$$

Note that $\left(\rho(0) + \rho(z_d)\right) g / 2$ represents an average water density within the column. The relationship between the water density and temperature is generally not linear. However, within the temperature range of interest (35^0C to 60^0C) it is very close to linear as is shown in Figure 6.2-4. The data plotted in this figure are from (Dean 1992, Table 5.14 [DIRS 100722]).

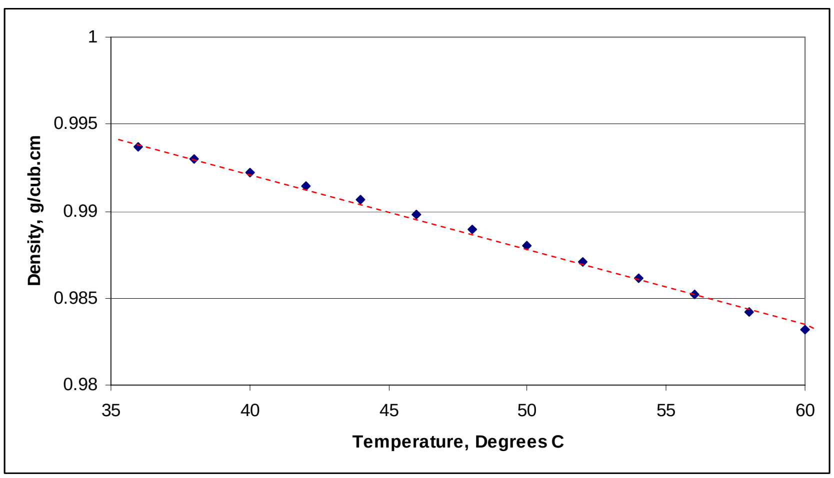


Figure 6.2-4 Density-Temperature Relationship

The temperature at the depth of 800 m (t_d) can be estimated as:

$$t_d = t_{wt}^0 + grad \cdot 800\ m$$

where t^0_{wt} is the ambient temperature at the water table (34^0C) and *grad* is the ambient average thermal gradient (25°C/km), (BSC 2004 [DIRS 170037], Section 6.5.3.7). The resulting temperature at a depth of 800 m is 54^0C. Consequently, the pressure at the bottom of the unheated vertical column can be written as:

$$p_w = z_d\left(\rho\left(T = 34^\circ C\right) + \rho\left(T = 54^\circ C\right)\right)g / 2$$

Based on the three-dimensional modeling the temperature at the water table under the repository will increase by 26.4^{0}C at 4,000 years, by 26.1^{0}C at 5,000 years and by 24^{0}C by 7,500 years. The corresponding temperature profiles and ambient temperature profiles are shown in Figure 6.2-5.

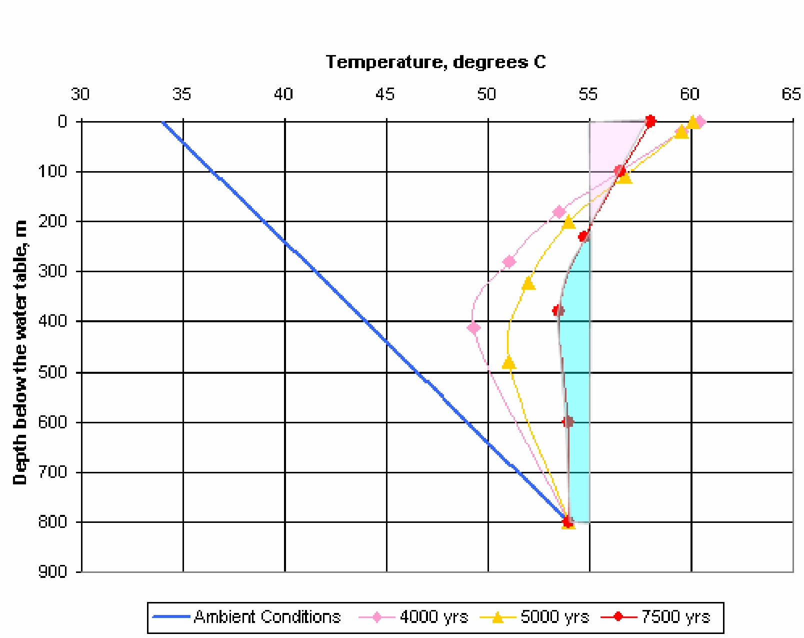


Figure 6.2-5. Temperature Profiles Under the Ambient and Repository Conditions

As can be seen from Figure 6.2-5, the most significant difference between the ambient and repository conditions with regard to water table mounding is at 7,500 years. The temperature within the first 100 m below the water table is higher at 4,000 and 5,000 years than at 7,500 years. However, everywhere else in the profile the temperatures at 7,500 years are higher. The average temperatures within the 800 m profile below the water table at 4,000 years, 5,000 years, and 7,500 years are 54^{0}C, 54.5^{0}C, and 55^{0}C respectively. Assuming the temperature everywhere within the 800 m profile will be 55^{0}C is a reasonable approximation. Figure 6.2-5 shows that, the shaded pink (top) area representing the underestimation of the changes in temperatures is smaller than the shaded blue (bottom) area representing the overestimation of these changes. Consequently, a constant temperature of 55^{0}C was assumed along the column profile.

The water pressure at the bottom of the vertical column under the repository will remain the same after heating, but the height of the column (z_{new}) will increase to reflect the increase in temperature and decrease in density. The increase can be found by equating the pressures under the repository with those of the ambient condition (the hydrostatic assumption):

$$p_w = z_d\left(\rho\left(T = 34^\circ C\right) + \rho\left(T = 54^\circ C\right)\right)g / 2 = z_{new}\rho\left(T = 55^\circ C\right)g$$

Rearranging the equation directly above, the following relationship can be obtained:

$$z_{new} = \frac{z_d \left(\rho\left(T = 34^\circ C\right) + \rho\left(T = 54^\circ C\right)\right)}{2\rho\left(T = 55^\circ C\right)}$$

The following data from Dean 1992, Table 5.14 [DIRS 100722] were used as input in the formula for z_{new} :

$\rho(T=34^0C)= 0.99437\ g/cm^3$

$\rho(T=54^0C)= 0.98618\ g/cm^3$

$\rho(T=55.1^0C)= 0.9856465\ g/cm^3$ (linear interpolation of numbers in Dean 1992 Table 5.14, [DIRS 100722]).

Using the equation for z_{new} results in a column height of 803.76 m. Consequently, the water table mounding resulting from peak temperature at the water table surface is 3.76 m. The hydraulic gradient in this area is 1.53×10^{-2}, calculated as follows, the difference in head between wells USW G-4 and USW G-1 is 23.6 m and the distance between these wells is 1547 m (DTN: GS010908312332.002 [DIRS 163555]). With an increase in head of 3.76 m due to the mounding of the water table, the difference in head between G-1 and G-4 increases to 27.36 m resulting in a hydraulic gradient of 1.77×10^{-2}. This increases the hydraulic gradient by a factor of 1.16. This additional increase in the hydraulic gradient resulting from the mounding of the water table is well within the uncertainty range for groundwater specific discharge (parameter name, GWSPD) which goes as high as a factor of 10 (BSC 2005 [DIRS 174012], Section 6.5.2.1).

In summary, the potential for convective flow to occur is decreased as a result of increasing temperatures from the repository. An increase in the temperature at the water table would decrease the value of the ΔT term in the Rayleigh expression, resulting in a smaller value for N_{RA} and a decrease in the potential for thermal convection. Mounding of the water table that may occur due to the repository serving as a heat source to the groundwater in the SZ results in a small increase to the existing hydraulic gradient as described above. Therefore, convective flow in the SZ due to waste emplacement will not significantly affect SZ flow paths. This FEP is excluded based on low consequence because it will not significantly change radiation exposure to the RMEI or radionuclide releases to the accessible environment.

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.35 Natural Geothermal Effects on Flow in the SZ (2.2.10.03.0A)

FEP Description: The existing geothermal gradient, and spatial or temporal variability in that gradient, may affect groundwater flow in the saturated zones.

Screening Decision: Included

Screening Argument: N/A

TSPA Disposition:

Natural geothermal effects, as they influence fluid properties, are implicitly included in the SZ site-scale flow model. Groundwater flow is simulated in the *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037]) using a conservation of fluid-rock energy equation in the numerical code FEHM. The fluid-rock energy equation is, in part, a function of permeability, density, viscosity, and temperature (BSC 2004 [DIRS 170037], Section 6.5.3.7). For temperatures that range between 20°C to 100°C, the density of water changes by only a few percent. In contrast, the variation in water viscosity changes by a factor of 3.3 over the same temperature range. Consequently, natural geothermal effects on groundwater flow are more effectively captured by spatially varying viscosity rather than density. The *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037], Section 6.5.3.7) assigns a specified temperature to each node, which varies with depth and is based on variable temperature measurements reported by Sass et al. (1988 [DIRS 100644]), using an average geothermal gradient. Temporal variations in the natural geothermal gradient are expected to be minor, as explained with regard to hydrothermal activity. Specifically, studies of two-phase fluid inclusions in the UZ at Yucca Mountain using petrography, microthermometry, and uranium-lead dating indicate that temperatures have remained close to the current ambient values over the past 2 million to 5 million years (Wilson et al. 2003 [DIRS 163589], Section 8). These findings show that significant or widespread alteration of the geothermal gradient has not occurred in the UZ in the recent geologic past, and suggest that such variations have been absent from the nearby SZ.

Permeability and viscosity are also assigned to each node. Temperatures are used to calculate nodal viscosities. Using the spatially varying viscosity, a fluid property, allows the calibration of hydraulic conductivity, a lumped fluid/rock property parameter. Estimated hydraulic conductivity at each node is calibrated to hydraulic head measurements, while nodal viscosities and temperatures remain fixed (BSC 2004 [DIRS 170037], Section 6.5.3.7). Hydraulic heads are, in part, manifestations of multiple processes within the system, including geothermal effects. By calibrating hydraulic conductivity to hydraulic heads and keeping spatially varying temperature and viscosity fixed, geothermal effects on flow are implicitly captured. The site-scale SZ transport model (BSC 2004 [DIRS 170036]) incorporates these effects by using the calibrated SZ site-scale flow model as its basis. Furthermore, the uncertainty that temperature may have on matrix diffusion is implicitly captured in the range for effective diffusion coefficients adopted in the SZ flow and transport model (BSC 2005 [DIRS 174012], Section 6.5.2.6).

Additionally, numerical simulations coupling heat transport and flow processes were performed using, as input, SZ temperature values in the SZ (BSC 2004 [DIRS 170037], Section 7.2.4). The results of the coupled thermal modeling provide a general independent validation of the SZ site-scale flow model and validate the implicit modeling of geothermal effects in SZ flow.

Supporting Reports:

- *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037])
- *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036])
- *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]).

6.2.36 Thermo-Mechanical Stresses Alter Characteristics of Fractures Near Repository (2.2.10.04.0A)

FEP Description: Heat from the waste causes thermal expansion of the surrounding rock, generating changes in the stress field that may change the properties (both hydrologic and mechanical) of fractures in the rock. Cooling following the peak thermal period will also change the stress field, further affecting fracture properties near the repository.

Screening Decision: Excluded–Low consequence

Screening Argument:

In the report *Features, Events, and Processes in UZ Flow and Transport* (BSC 2005 [DIRS 174191], Section 6.9.10), it is concluded that thermally induced stresses would have no long-term effect on rock and fracture properties above and below the repository that would affect long-term UZ flow and transport. Specifically, thermally induced stresses would tend to reduce UZ fracture permeabilities and effectively reduce UZ transport times below the repository.

The effects of thermal loading due to waste emplacement on fractures within the vicinity of the repository drifts are evaluated in *Mountain-Scale Coupled Processes (TH/THC/THM)* (BSC 2005 [DIRS 174101], Section 6.5). At 10,000 years, when the repository is well into a cooling phase, thermal-mechanical stresses do not impart significant changes in vertical and horizontal fractures beyond 100 m below the repository (BSC 2005 [DIRS 174101], Figures 6.5.12-1 and 6.5.12-2). Because the top of the SZ is approximately 335 m below the repository (DTN: GS000808312312.007 [DIRS 155270], Table S00397 001; CRWMS M&O 2000 [DIRS 153246], Figure 3.2-10), it is inferred that the effects of the thermally induced changes in the mechanical and hydrologic properties of SZ fractures will be insignificant during the cooling phase of the thermally induced stress pulse.

An evaluation of the peak temperature and stress changes at the water table was also performed, using a three-dimensional model of heat transfer as described in Appendix C of this report. These calculations, conclude that thermal-mechanical stresses at the water table are not enough to produce a compressional stress that would significantly affect fracture permeability in the SZ.

To summarize, thermal-mechanical stresses cause few to no changes in horizontal hydrologic and mechanical properties in fractures located 100 m or more below the repository. Changes in vertical fracture properties are affected by thermal loading but decrease with distance and are minimal at elevations 100 m below the repository. Because the top of the SZ is approximately 335 m below the repository, it is inferred that the effects of the thermal-mechanical induced stress changes will have little to no effect on SZ fractures.

In conclusion, thermal-mechanical stresses imposed on fractures within the vicinity of the repository have little to no effect on SZ fractures properties. Additionally, thermal-mechanical stresses are excluded in the UZ near-field, by deduction, the thermal-mechanical stress "pulse" will have less of an impact further out in the region of the SZ. Thermal-mechanical stresses on fractures in the SZ are excluded based on low consequence because they will not significantly change radiation exposure to the RMEI or radionuclide releases to the accessible environment.

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.37 Thermo-Mechanical Stresses Alter Characteristics of Faults Near Repository (2.2.10.04.0B)

FEP Description: Heat from the waste causes thermal expansion of the surrounding rock, generating changes to the stress field that may change the properties (both hydrologic and mechanical) in and along faults. Cooling following the peak thermal period will also change the stress field, further affecting fault properties near the repository.

Screening Decision: Excluded–Low consequence

Screening Argument:

In the report *Features, Events, and Processes in UZ Flow and Transport* (BSC 2005 [DIRS 174191], Section 6.9.11), it is concluded that thermally induced stresses would have no long-term effect on fault properties that would affect long-term UZ flow and transport. Because thermal-mechanical stresses are excluded in the UZ, by deduction, the thermal-mechanical stress "pulse" will have less of an impact further out in the region of the SZ.

For purposes of assessing the thermal-mechanical stresses on SZ faults due to waste emplacement, SZ faults can be considered as large fractures. Therefore, it is appropriate to review the impacts of thermal-mechanical stresses on fractures in order to understand similar stress effects on faults. The effects of thermal-mechanical loading due to waste emplacement on fractures within the vicinity of the repository drifts are evaluated in *Mountain-Scale Coupled Processes (TH/THC/THM)* (BSC 2005 [DIRS 174101], Section 6.5). Results indicate the highest thermally induced stresses occur at approximately 100 years within the repository horizon, are horizontal in direction, and are compressive in nature below the repository (BSC 2005 [DIRS 174101], Figure 6.5.11-1). Moving away from the repository, stresses dampen. Above the repository, thermally induced stresses are both compressive and tensile in nature (BSC 2005 [DIRS 174101], Section 6.5.11). Compressive stresses transition to tensile stresses at approximately 260-330 m above the repository. Changes from compressive to tensile stresses are not seen below the repository. Model results indicate thermal-mechanical stresses induced from waste emplacement do not significantly affect SZ vertical and subvertical and horizontal fracture hydrologic properties (FEP 2.2.10.04.0A– Thermo-mechanical stresses alter characteristics of fractures near repository).

An evaluation of the peak temperature and stress changes at the water table was also performed, using a three-dimensional model of heat transfer as described in Appendix C of this report. The calculations, (see Appendix C) concluded that thermal-mechanical stresses at the water table are not enough to produce a compressional stress that would significantly affect fracture permeability (or faults) in the SZ.

Faults in the SZ are further from the heat source (the repository), are larger than fractures, and extend deep into the SZ. A fault's response to the same thermally induced stresses imposed on fractures will be mitigated due to its size and distance from the heat source. If thermally induced mechanical stresses will not affect fracture hydrologic properties in the SZ, they will not affect fault properties within the SZ either.

In summary, thermal-mechanical stresses from waste emplacement imposed on faults located in the SZ are excluded due to low consequence, because they will not significantly change radiation exposure to the RMEI or radionuclide releases to the accessible environment.

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.38 Thermo-Mechanical Stresses Alter Characteristics of Rocks Above and Below the Repository (2.2.10.05.0A)

FEP Description: Thermal-mechanical compression at the repository may produce tension fracturing in the Paintbrush non-welded tuff and other units above the repository. These fractures may alter unsaturated zone flow between the surface and the repository. Extreme fracturing may propagate to the surface, affecting infiltration. Thermal fracturing in rocks below the repository may affect flow and radionuclide transport to the saturated zone.

Screening Decision: Excluded–Low consequence

Screening Argument:

An evaluation of the change in temperature and the thermally induced stress at the water table was peformed using a three-dimensional model of heat transfer described in Appendix C of this report. Based on these calculations it can be concluded that at the water table thermal-mechanical stresses are not enough to produce a compressional stress that would significantly affect fracture permeability in the SZ (see FEP 2.2.10.04.0A–Thermo-mechanical stresses alter characteristics of fractures near repository). Since fractures are more susceptible to thermally induced stresses than the rock matrix and, at the water table, their hydrologic properties are not significantly affected by compressive stresses, then it is inferred neither will matrix hydrologic properties be affected by thermally induced stresses (see FEP 2.2.10.04.0A-Thermo-mechanical stresses alter characteristics of fractures near repository).

Additionally, thermal-mechanical stresses affect the near-field environment to a greater extent than the far-field region, the province of the SZ. Thermal-mechanical stresses on the UZ rock properties are excluded in the UZ (BSC 2005 [DIRS 174191], Section 6.9.12). By deduction, thermal-mechanical stresses will have less of an effect in the far-field and should be excluded as well.

Thermal-mechanical stress in the units above the repository is a UZ issue and outside the province of the SZ. A screening decision with respect to thermal fracturing of these units is found in *Features, Events, and Processes in UZ Flow and Transport* (BSC 2005 [DIRS 174191], Section 6.9.12).

In summary, thermal-mechanical stresses on the SZ rock properties are excluded due to low consequence, because they will not significantly change radiation exposure to the RMEI or radionuclide releases to the accessible environment.

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.39 Thermo-Chemical Alteration in the SZ (Solubility, Speciation, Phase Changes, Precipitation/Dissolution) (2.2.10.08.0A)

FEP Description: Thermal effects may affect radionuclide transport directly by causing changes in radionuclide speciation and solubility in the SZ, or, indirectly, by causing changes to host rock mineralogy that affect the flow path. Relevant processes include volume effects associated with silica phase changes, precipitation and dissolution of fracture filling minerals (including silica and calcite), and alteration of zeolites and other minerals to clays.

Screening Decision: Excluded–Low consequence

Screening Argument:

SZ water temperatures at the water table and below the repository footprint may increase due to waste emplacement. An estimate of the potential temperature increase is predicted with a three-dimensional heat transfer calculation (Appendix C of this report). Temperature changes at the water table are estimated to peak at approximately 26°C above the initial temperature around 4000 years after waste emplacement. If temperatures at the water table do reach these upper-bounding estimates the thermal impact on host rock mineralogy and water chemistry will not affect the SZ barrier capability for the following reasons. CO_2 becomes less soluble at elevated temperatures. Small changes in CO_2 concentrations greatly affect pH variability. These two constituents are the primary components that affect mineral/water interactions (BSC 2005 [DIRS 174101], Section 6.4.3.3). Therefore, as temperatures increase, CO_2 would exsolve out of solution, causing pH to rise and calcite to precipitate in pores and fractures. Calcite precipitation in pores and along fractures would decrease permeability. Once temperatures start to drop, CO_2 dissolution increases and pH decreases, causing calcite that precipitated in pores and fractures at elevated temperatures to dissolve, and concomitant permeabilities to return to those in effect under ambient conditions. Thus, an increase SZ groundwater temperatures would not affect SZ barrier capability.

Mineral-water reactions cause vitric and silica-bearing minerals to degrade to zeolites and other secondary minerals, including clays. These minerals have a high sorption capacity. Zeolites tend to have the highest porosity and sorption capacity of all the secondary minerals found at Yucca Mountain. It is inferred similar thermally induced mineral alteration would cause degradation of silicic and vitric minerals to zeolites and other clays in the SZ in the proximity of the water table. In the *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036] no credit is being taken for sorption onto zeolites that reside along the SZ flow path (BSC 2004 [DIRS 170036], Table 6.6-1b). Consequently, any possible alteration of zeolites in the SZ will not adversely affect the SZ barrier capability.

Groundwater flow enters the SZ site-scale flow system primarily as underflow at the lateral boundaries of the model domain (BSC 2005 [DIRS 174012], Section 6.3.1), with SZ distributed recharge primarily in the northern part of the model domain, and focused recharge along the Fortymile Wash channel. Recharge from the UZ along the SZ transport abstraction model domain constitutes a small fraction of the entire groundwater budget of the site-scale flow system (BSC 2005 [DIRS 174012], Section 6.3.1). Relative to the total water budget in the SZ flow domain the distributed recharge from the UZ to SZ is approximately 7% of total recharge (BSC 2004 [DIRS 170015], Table 6-4). Therefore, thermally induced changes in SZ water chemistry would be diluted given the relatively small volume of UZ water that is contributed to total volume of water that passes through the SZ flow system.

In the case of no mixing, the analysis presented in *Features, Events, and Processes in UZ Flow and Transport* (BSC 2005 [DIRS 174191], Section 6.9.13) is relevant. This analysis considers the effects of thermal-hydrological-chemical (THC) processes on radionuclide transport in terms of radionuclide solubility, colloid stability, water composition, mineral precipitation and dissolution, and temperature. The results of this analysis indicate that the effects of THC processes on radionuclide transport between the repository to the water table are negligible. Therefore, the effects THC processes on water composition entering the SZ from the UZ will also have a negligible effect on radionuclide transport in the SZ.

The *SZ Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]) does not implement a solubility limit for each transported radionuclide. The radionuclide concentration that is introduced into the SZ from the UZ is unconstrained. Furthermore, radionuclides introduced in the UZ from the EBS are also unconstrained; that is, the solubility is not reduced as radionuclides go from the higher temperature repository conditions to the UZ. Therefore, SZ temperature variability on radionuclide solubility will have no effect on radionuclide transport in the SZ.

In the report *Features, Events, and Processes in UZ Flow and Transport* (BSC 2005 [DIRS 174191], Section 6.9.14), thermal-chemical effects on alteration in the Calico Hills unit are evaluated. That analysis indicates thermal-chemical effects are limited to the near-field environment and are of short duration, which will not have a significant effect on UZ contaminant transport or the release to the accessible environment. Because thermal-chemical effects are excluded in the near-field, by deduction, the thermal-chemical alteration will have less of an impact further out in the region of the SZ and are also excluded there. All of these reasons support excluding this FEP due to low consequence, because it will not significantly change radiation exposure to the RMEI or radionuclide releases to the accessible environment.

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.40 Repository-Induced Thermal Effects on Flow in the SZ (2.2.10.13.0A)

FEP Description: Thermal effects in the geosphere could affect the long-term performance of the disposal system, including effects on groundwater flow (e.g., density-driven flow), mechanical properties, and chemical effects in the SZ.

Screening Decision: Excluded–Low consequence

Screening Argument:

Numerical modeling of the mountain-scale effects of thermal loading on the host rock due to waste emplacement is evaluated in *Mountain-Scale Coupled Processes (TH/THC/THM)* (BSC 2005 [DIRS 174101], Section 6.5). Model results indicate that the host rock temperatures at the drift wall are about 100°C at approximately 1,000 years after waste emplacement (BSC 2005 [DIRS 174101], Figure 6.5.10-2). These elevated temperatures produce a long term heat pulse that originates at the repository and propagates outwards.

To evaluate the change in temperature and the thermally induced stress at the water table an evaluation of these changes was done using a three-dimensional model of heat transfer described in Appendix C of this report. These calculations show that at the water table temperature peaks at approximately 4,000 years with the maximum temperature equal to 60ºC (see Figure C-3 of this report), which is a 26ºC increase in comparison with the ambient temperature of 34°C specified at the water table beneath the repository (Appendix C of this report). Ambient SZ water temperatures at the water table along the transport path range between 30°C and 34°C (Fridrich et al. 1994 [DIRS 100575], Figure 8). Furthermore, SZ ambient temperatures increase with depth along the transport path, with some temperatures as high as 40°C–45°C in units where transport takes place (measured in well UE-25p#1, DTN MO0102DQRBTEMP.001 [DIRS 154733]). The change in temperature due to the waste emplacement is comparable with the ambient variability in temperature, thus the effects on flow should be similar as well.

As temperatures increase CO_2 could exsolve out of solution, causing pH to rise and calcite to precipitate in pores and fractures. However, recharge from the UZ along the SZ transport abstraction model domain constitutes a small fraction of the entire groundwater budget of the site-scale flow system (BSC 2005 [DIRS 174012], Section 6.3.1). Relative to the total water budget in the SZ flow domain the distributed recharge from the UZ to the SZ is approximately 7% of total recharge (BSC 2004 [DIRS 170015], Table 6-4. Therefore, thermally induced changes in SZ water chemistry would be diluted given the relatively small volume of UZ water that is contributed to total volume of water that passes through the SZ flow system. Sorption is a temperature dependent process and increases as temperature increases. An increase in groundwater temperatures would increase the sorption capacity of the transported radionuclides, thus retarding transport to the accessible environment. In the SZ models, radionuclide partitioning coefficients are based on ambient SZ temperatures and are not temperature-dependent. An increase in sorption capacity due to an increase in SZ water temperatures would tend to increase SZ transport times. Thus, including the effects of elevated SZ groundwater temperatures would not have an adverse effect on performance.

Radionuclide-bearing waters at elevated temperatures would be less dense than ambient waters. Density and temperatures gradients, together, would promote lateral dispersion along the transport path. Lateral dispersion would facilitate matrix diffusion (i.e., physical retardation) as the plume extends laterally along a wider transport path, reducing transport times and radionuclide peak concentrations. The combination of the above conditions in the SZ transport model would both increase transport times and reduce peak concentrations, thus reducing peak exposure to the RMEI. Therefore, temperature-induced density effects would not have an adverse effect on performance. Repository-induced thermal effects on SZ mechanical properties are discussed in FEP 2.2.10.05.0A - Thermo-Mechanical Stresses Alter Characteristics of Rocks Above and Below the Repository.

All of the above support the conclusion that repository-induced thermal effects on flow in the SZ can be excluded due to low consequence because they will not significantly change radiation exposure to the RMEI or radionuclide releases to the accessible environment.

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.41 Gas Effects in the SZ (2.2.11.01.0A)

FEP Description: Pressure variations due to gas generation may affect flow patterns and contaminant transport in the SZ. Degassing could affect flow and transport of gaseous contaminants. Potential gas sources include degradation of repository components and naturally occurring gases from clathrates, microbial degradation of organic material, or deep gases in general.

Screening Decision: Excluded–Low consequence

Screening Argument:

The effects of gas pressurization are excluded on several bases. There is no evidence of large-scale gas buildup in, or flow of gas through, the SZ. Additionally, no significant volumes of oil or gas have been found in the Yucca Mountain vicinity, and proven source rocks in the region are lacking (French 2000 [DIRS 107425], p. 5). While the geologic elements required for a petroleum system are present in the Yucca Mountain region, stratigraphic seals (important in a viable hydrocarbon producing region) are not well developed in the Yucca Mountain area, causing the hydrocarbon potential to be classified as low (French 2000 [DIRS 107425], p. 39).

In the unlikely event that gas-generating processes occur in the sedimentary rocks below the tuffs, the influence on the flow and transport pathways would tend to be highly localized. Given the coarse grid used in the flow model and the uncertainty in the flow and transport pathways incorporated in the model, undetected localized processes or features that divert flow would either be too small in scale to impact the simulations or would be accounted for in the heterogeneity and parameter uncertainties in the SZ flow and transport model. As a result, gas-generating processes would not have a significant effect on the effective model parameter values and therefore would not affect radionuclide release to the accessible environment.

The presence of clathrates and microbial degradation of organic components are two potential sources of gas that may affect flow and transport in the SZ. Clathrates, methane gas molecules bound in a cage-like structure made up of water molecules, form under high pressures and low temperatures. Clathrates are found in polar and deep oceanic regions (Kvenvolden 1998 [DIRS 166162], pp. 9 to 11). Clathrates are not a potential hydrocarbon source in the Yucca Mountain vicinity since low-temperature, high-pressure conditions do not exist in the region.

Microbial degradation of organic components is not considered a potential gas source in the SZ. Analysis of groundwater samples taken from SZ wells within the Yucca Mountain vicinity have found little to no organic carbon (DTN: GS931100121347.007 ([DIRS 149611], Table S96375 009); DTN: GS010308312322.003 ([DIRS 154734], Table S01053 003); DTN: GS011108312322.006 [DIRS 162911]). Organic carbon is a biproduct of microbial activity. Because there is little organic carbon found in SZ waters, there is insignificant microbial activity in the SZ producing CO_2 gas that would affect SZ flow and transport.

Because the repository is situated in the UZ approximately 335 m above the water table (DTN: GS000808312312.007 [DIRS 155270], Table S00397 001; CRWMS M&O 2000 [DIRS 153246], Figure 3.2-10), degradation of repository components that would potentially produce gas will not affect flow and transport in the SZ. A screening decision related to gas production from repository components as it affects UZ flow and transport is found in *Features, Events, and Processes in UZ Flow and Transport* (BSC 2005 [DIRS 174191], Section 6.7.2).

In summary, the potential effects of naturally occurring gases in the geosphere can be excluded from the SZ flow and transport model based on low consequence, because they will not significantly change radiation exposure to the RMEI or radionuclide releases to the accessible environment.

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.42 Undetected Features in the SZ (2.2.12.00.0B)

FEP Description: Undetected features in the SZ portion of the geosphere can affect long-term performance of the disposal system. Undetected but important features may be present, and may have significant impacts. These features include unknown active fracture zones, inhomogeneities, faults and features connecting different zones of rock, and different geometries for fracture zones.

Screening Decision: Included

Screening Argument: N/A

TSPA Disposition:

Undetected features in the SZ, such as fracture zones, inhomogeneities, faults, gravel lenses and channels in the alluvium, and their potential impacts on groundwater flow are implicitly incorporated in the SZ transport abstraction model and the SZ one-dimensional transport model through parameter distributions (BSC 2005 [DIRS 174012]); both models are described in the report by BSC (2005 [DIRS 174012], Section 6.3). The generation of multiple flow and transport realizations, using stochastically sampled key parameters as input, significantly varies flow and transport pathways in the SZ.

Modeling of natural processes is, in many instances, based on using lumped parameters. Lumped parameters are parameters that are based on empirical observations (i.e., not all processes or first order physics are explicitly understood or known). Hydraulic conductivity, permeability, and transmissivity are examples of lumped parameters. In matching hydraulic heads (a response to the system) with variable lumped parameters such as permeability, one implicitly incorporates undetected features into the model (BSC 2004 [DIRS 170037], Section 6.6.1). The site-scale SZ transport model (BSC 2004 [DIRS 170036]) incorporates these effects by using the calibrated SZ site-scale flow model as its basis.

Groundwater specific discharge in the SZ may be enhanced due to the presence of undetected features. In the alluvium features could be undetected gravel lenses and channels, and in the volcanic units these could be undetected faults and fractures or fracture clusters. Uncertainty in parameters related to these features are applied to the hydrogeologic units defined in the hydrogeologic framework model documented in *Hydrogeologic Framework Model for the Saturated Zone Site Scale Flow and Transport Model* (BSC 2005 [DIRS 174109]). Uncertainty in groundwater specific discharge in the SZ is based on data gathered from single- and multiwell hydrologic testing in the volcanic units near Yucca Mountain and field testing in the alluvium at the alluvial tracer complex. In the TSPA, the GWSPD parameter is a multiplication factor applied to all SZ permeability values and specified boundary fluxes (BSC 2005 [DIRS 174012], Section 6.5.2.1) to effectively scale the simulated specific discharge and implicitly model the effects undetected features may have on groundwater specific discharge. Uncertainty in the flowing interval spacing parameter (BSC 2004 [DIRS 170014]) implicitly accounts for smaller-scale undetected features that transmit significant quantities of groundwater in the SZ. The assessment of horizontal anisotropy in permeability, as documented in *Saturated Zone*

In-Situ Testing (BSC 2004 [DIRS 170010]), potentially includes the effects of preferentially oriented undetected features on groundwater flow in the SZ.

The key parameters that implicitly model undetected features (BSC 2005 [DIRS 174012]) are (1) GWSPD, (2) HAVO, (3) FISVO, (4) LDISP, and (5) sorption coefficients (K_d) for 9 the classes of radionuclides modeled in both the alluvium and volcanic units (parameters are described in *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012], Sections 6.5.2.1, 6.5.2.9, 6.5.2.10, 6.5.2.4, and 6.5.2.8 and Table 6-8).

Additional parameters that model undetected SZ features are FPVO, LDISP incorporated in both the volcanic units and the alluvium, effective porosity in the alluvium units 7 and 19 (NV7 and NV19), and alluvium bulk density (bulk density). Additionally, in the SZ transport abstraction model (BSC 2005 [DIRS 174012], Section 6.5.2.2), undetected features are accounted for through the probabilistic boundaries of the alluvium uncertainty zone. The western and northern boundaries of the alluvium uncertainty zone are defined with the sampled parameters FPLAW and FPLAN. The above parameters that implicitly model undetected features are described in *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012], Sections 6.5.2.1, 6.5.2.2, 6.5.2.10, 6.5.2.4, 6.5.2.5, 6.5.2.7, 6.5.2.3, 6.5.2.8, respectively).

Supporting Reports:

- *Hydrogeologic Framework Model for the Saturated Zone Site-Scale Flow and Transport Model* (BSC 2005 [DIRS 174109]).
- *Probability Distribution for Flowing Interval Spacing* (BSC 2004 [DIRS 170014]).
- *Saturated Zone Site-Scale Flow Model* (BSC 2004 [DIRS 170037]) (While FEP 2.2.12.00.0B is not explicitly identified in this report (BSC 2004 [DIRS 170037], Table 6-1), the FEP is addressed in the report).
- *Site-Scale Saturated Zone Transport* (BSC 2004 [DIRS 170036]).
- *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]).
- *Saturated Zone In-Situ Testing* (BSC 2004 [DIRS 170010]).

6.2.43 Groundwater Discharge to Surface Outside the Reference Biosphere (2.3.11.04.0A)

FEP Description: Radionuclides transported in groundwater as solutes or solid materials (colloids) from the far-field may discharge at specific “entry” points that are outside the reference biosphere. Natural surface discharge points, including those resulting from water table or capillary rise, may be surface water bodies (rivers, lakes), springs, wetlands, holding ponds, or unsaturated soils.

Screening Decision: Excluded–by regulation

Screening Argument:

The reference biosphere is defined as the description of the environment inhabited by the RMEI (10 CFR 63.2 [DIRS 173273]). FEPs that describe the reference biosphere are those that affect the RMEI. Conversely, FEPs that occur outside the reference biosphere do not affect the RMEI's exposure and are not included. The postclosure individual protection standard is formulated in terms of annual doses to the RMEI (10 CFR 63.311 [DIRS 173273]). Because the performance assessment uses the characteristics of the reference biosphere to demonstrate compliance with the individual protection standard (66 FR 55732 [DIRS 156671], p. 55784) the FEPs related to any processes occurring outside the reference biosphere are implicitly excluded. Therefore, groundwater discharge to surface outside the reference biosphere is excluded on the basis of inconsistency with the requirements for demonstration of compliance with the postclosure performance objectives (10 CFR 63.113(b) [DIRS 173273]).

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.44 Radioactive Decay and Ingrowth (3.1.01.01.0A)

FEP Description: Radioactivity is the spontaneous disintegration of an unstable atomic nucleus that results in the emission of subatomic particles. Radioactive species (isotopes) of a given element are known as radionuclides. Radioactive decay of the fuel in the repository changes the radionuclide content in the fuel with time and generates heat. Radionuclide quantities in the system at any time are the result of the radioactive decay and the ingrowth of decay products as a consequence of that decay. Over a 10,000-year performance period, these processes will produce decay products that need to be considered in order to adequately evaluate the release and transport of radionuclides to the accessible environment.

Screening Decision: Included

Screening Argument: N/A

TSPA Disposition:

Radioactive decay during transport in the SZ is explicitly included in the convolution integral method used to couple the SZ transport abstraction model with the TSPA model and in the SZ 1-D transport model (both models are described in *SZ Flow and Transport Model Abstraction* BSC 2005 [DIRS 174012], Section 6.3). Ingrowth is accounted for in two different ways in the TSPA models. First, the radionuclide mass entering the SZ at the water table is adjusted to account for the potential ingrowth of some radioactive decay products, resulting in a "boosting" of the initial inventory of some radioactive decay products (BSC 2005 [DIRS 174012], Section 6.3.1). This approach is a conservative simplification that overestimates the mass of these radioactive decay products being transported in the SZ. Second, a separate set of SZ transport simulations is run to calculate explicitly the decay and ingrowth for the four main radionuclide chains, using the SZ one-dimensional transport model (BSC 2005 [DIRS 174012], Section 6.3.2 and 6.5.1.2). These two ways of accounting for ingrowth in the SZ transport simulations differ from the approach used in the UZ transport simulations because of the differing numerical methods used. The convolution integral method, as implemented in the SZ transport abstraction model, is not able to explicitly calculate radioactive ingrowth and transport radioactive decay products. Consequently, the simplified approach of decay product source "boosting" is used for some direct radioactive decay products, and the SZ one-dimensional transport model is used for the longer decay chains.

Supporting Reports:

- *Saturated Zone Flow and Transport Model Abstraction* (BSC 2005 [DIRS 174012]).

6.2.45 Isotopic Dilution (3.2.07.01.0A)

FEP Description: Mixing or dilution of the radioactive species from the waste with species of the same element from other sources (i.e., stable and/or naturally occurring isotopes of the same element) could lead to a reduction of the radiological consequences.

Screening Decision: Excluded–Low consequence

Screening Argument:

Isotopic dilution in the SZ could occur if elements that are in the waste also occur naturally. Prime examples of naturally occurring isotopes in SZ groundwaters are those of strontium (^{84}Sr, ^{86}Sr, ^{87}Sr, ^{88}Sr), uranium (^{234}U and ^{238}U), and carbon (^{12}C and ^{13}C) (BSC 2004 [DIRS 170037], Appendix A, Table A4-1). In the SZ flow and transport model the concentration of radionuclides released from the UZ to the SZ is not diluted due to the presence of naturally occurring isotopes such as those listed above. Isotopic dilution would dilute the concentration of radioactive contaminants in the groundwater withdrawn from wells in the hypothetical farming community, thus reducing radiological exposure to the RMEI. Therefore, isotopic dilution is excluded based on low consequence, because it has no adverse effects on performance.

TSPA Disposition: N/A

Supporting Reports: N/A

6.2.46 Recycling of Accumulated Radionuclides from Soils to Groundwater (1.4.07.03.0A)

FEP Description: Radionuclides that have accumulated in soils (e.g. from deposition of contaminated irrigation water) may leach out of the soil and be recycled back into the groundwater as a result of recharge (either from natural or agriculturally induced infiltration). The recycled radionuclides may lead to enhanced radionuclide exposure at the receptor.

Screening Decision: Excluded–by regulation

Screening Argument:

The applicable regulations do not require consideration of the irrigation-recycling process in calculating the dose to the RMEI under 10 CFR 63.311 [DIRS 173273]. See Ziegler (2004 [DIRS 172234]) for a complete discussion of the regulatory screening argument for this FEP. The SZ FEPs relate to natural conditions and do not include human-induced changes to radionuclide transport and concentration, as postulated in irrigation recycling. In any event, a sensitivity study to evaluate the maximum impacts that could occur as a result of irrigation recycling shows that the irrigation recycling phenomenon is of low consequence (see Supplemental Discussion). Therefore, it is not a significant FEP and can be excluded per 10 CFR 63.114(e) [DIRS 173273].

The performance assessment is an analysis that identifies and examines the effects of FEPs on the "Yucca Mountain disposal system" as defined in 10 CFR 63.2 [DIRS 173273]. The "Yucca Mountain disposal system" includes natural barriers that prevent or substantially reduce releases from the waste. The saturated zone is one of these natural barriers but does not include the reference biosphere, which is defined as the description of the environment inhabited by a hypothetical receptor. Pursuant to 10 CFR 63.102(j) [DIRS 173273], each FEP to be analyzed in the performance assessment relates to the effect of natural conditions, rather than human activities, on the performance of the engineered and/or the natural barrier systems. As described by the U.S. Environmental Protection Agency in estimating the dose incurred by the RMEI, the "exposure variations are calculated as a function of the parameters that control radionuclide transport from the contamination source (here, the repository)" (66 FR 32074 [DIRS 155216], p. 32089). In other words, the dose the RMEI is projected to receive is derived solely from the performance of the repository as affected by the identified FEPs and is not to take into account any potential human-induced changes to the geosphere. Conversely, there is no indication in the regulations that, once the radionuclides are transported to the compliance point, any human-induced changes are to affect the delivered concentration

At present, there is no human behavior, including irrigated farming, affecting the groundwater between the proposed location of the repository and the 18-km compliance location, or at the 18-km compliance location itself. In order to avoid the interjection of speculation that cannot be scientifically documented and analyzed, 10 CFR 63.305 [DIRS 173273] prohibits the projection of changes in society or the biosphere (other than climate). As a consequence, to avoid speculation regarding the existence or nature of future human activities, no assumptions are made regarding future sites of cultivation or future farming and irrigation practices within the controlled area between the repository and the 18-km compliance location or at the 18-km compliance location. Human activity that has the potential to affect performance of the engineered and natural barrier system is taken into account only in conjunction with determining compliance with the single stylized human intrusion scenario set forth in the separate individual protection standard of 10 CFR 63.321 [DIRS 173273]. By specifying this single instance of human interference and no others, the NRC regulations indicate that no other forms of human interference, including irrigated farming, are to be considered.

TSPA Disposition: N/A

Supporting Reports: N/A

Supplemental Discussion:

If human-induced changes to the geosphere were to be considered, a sensitivity analysis confirms that the postulated process of irrigation recycling would not result in total recapture of radionuclides, and not result in simulated doses that are significantly greater. Losses of radionuclide mass from a "closed" recycling system would occur from nonagricultural uses of groundwater and non-capture of contaminated recharge by receptor wells. The steady-state solution for a recycling system with losses indicates that contaminant concentrations (discounting radioactive decay) would be the same or not greater than a factor of 1.5, relative to concentrations with no recycling, in four potential scenarios. Derivation of the steady-state solution for radionuclide recycling is presented in Appendix B.

The ratio of radionuclide concentration in a receptor well for a "closed" system (with two loss mechanisms considered, as discussed above) to the open system receptor well concentration is given by the following equation (see attachment for derivation).

$$\frac{C_w}{C_{w-O}} = \frac{1}{\left[1 - F_c \, F_i\right]} \qquad \text{(Eq. 6-5)}$$

Where: C_w = The concentration in the receptor well (Ci/m^3) assuming the system is "closed" with two loss mechanisms considered.

C_{w-o} = The concentration in the receptor well (Ci/m^3) assuming the system is open.

F_c = The fraction of recycled water that is recaptured by the wells.

F_i = The fraction of the total water demand that is used for agricultural irrigation.

The characteristics of the RMEI and the reference biosphere lead to a set of assumed scenarios for use in this sensitivity analysis, consistent with 10 CFR 63.312 and 63.305 [DIRS 173273], respectively. Estimates of the "closed to open system" ratio are used to evaluate the potential impacts of recycling.

The RMEI meets the requirements of 10 CFR 63 [DIRS 173273] in all scenarios. In its background information to 40 CFR Part 197 (66 FR 32074 [DIRS 155216], p. 32112), the EPA assumed in its determination of the 3,000 acre-ft/year representative volume that 2550 acre-ft/year is for agricultural use, 100 acre-ft/year for commercial/industrial water use, and 120 acre-ft/year for individual/municipal water use. Therefore, for all scenarios it is assumed that 92 percent of the representative volume is used for irrigation and other uses that potentially can contribute to recycling (F_i = 0.92).

Each scenario below provides an estimate of the fraction of recycled water that is recaptured by withdrawal wells. These recapture fractions are based on general hydrologic properties and do not explicitly consider well capture properties (i.e., cone of influence). Explicit consideration of these properties is expected to reduce the likelihood that such wells would recapture recycled contaminant. The "closed to open system" ratio is determined by comparing pumping demands to the aquifer water budget. This ratio represents the likelihood that recycled water is not recaptured by the withdrawal well. This approach considers features such as that irrigation is applied at a distance from the pumping location and the contaminant plume.

These sensitivity analyses are simplified and conservative, bounding analyses that do not account for all of the other enumerated loss mechanisms or for other realistic circumstances that would further reduce the predicted radionuclide concentrations. These analyses do not, in effect, represent systems that are entirely "open," and instead focus on two significant loss mechanisms to provide a more realistic evaluation of the potential impacts of recycling. The scenarios do not take into account additional mitigating effects such as crop rotation and the properties of withdrawal wells, either of which would reduce the ratios discussed below. In addition, the estimates of "closed to open system" ratios are based on current conditions. Future climate states are expected to be wetter, resulting in increased aquifer flow rates, reduced irrigation requirements, and lower recapture fractions. These additional assumptions and loss mechanisms would further reduce any potential impacts of recycling.

Scenario 1: Locally Grown Food Produced at Current Location Using Well Water Withdrawn at that Location

In this scenario, locally grown food consumed by the receptor is assumed to be produced in its current location, approximately 30 km downgradient from the repository in the Town of Amargosa Valley. All water used to produce this food is assumed to be withdrawn at that location. Two cases are considered.

The first case assumes that the concentration of radionuclides withdrawn at 30 km is conservatively assumed to be the same as the highest concentration at 18-km and the representative volume is 3,000 acre-ft/year. This case is clearly conservative since the annual pumping demand at the 30 km location is approximately 14,000 acre-ft/year (as estimated for 1997) and the total water budget for the Amargosa Desert hydrologic basin is on the order of 40,000 acre-ft/year (66 FR 32074 [DIRS 155216], p. 32113).

The second, and more realistic case, considers a 14,000 acre-ft/year water demand. A significant amount of dilution and dispersion would occur between the 18-km and 30-km locations, but is not explicitly included in this analysis which only focuses on capture fractions.

In either case, the larger number of farms in this area would effectively spread any contaminant across a fairly large area, minimizing the amount of "recycled" contaminant that would be recaptured in the wells. Capture fractions can be estimated using both the representative volume (3,000 acre-ft/year) and the actual water demand (14,000 acre-ft/year) as compared to the water budget within the Amargosa Desert hydrologic basin (40,000 acre-ft/year).

Use of the 3,000 acre-ft/year representative volume yields a capture fraction of approximately 7.5 percent (3,000 acre-ft/year / 40,000 acre-ft / year) and a "closed to open system" ratio of 1.07. Using a capture fraction of 35 percent (14,000 acre-ft/year / 40,000 acre-ft/year) yields a "closed to open system" ratio of 1.5. However, although the "closed to open system ratio" is larger in the case of the 14,000 acre-ft/year water demand, the open system radionuclide concentration would be significantly smaller due to dilution and dispersion loss mechanisms not taken into account in this analysis.

Scenario 2: Locally Grown Food Produced at Current Location Using Well Water Withdrawn at the 18-km Compliance Point

In this scenario, locally grown food consumed by the receptor is assumed to be produced in its current location, 30 km downgradient from the repository in the Town of Amargosa Valley. All water used to produce this food is assumed to be withdrawn at the 18-km compliance location. Well water would be used to irrigate crops a considerable distance downgradient from the withdrawal point. Because the irrigation would occur at 30 km from the repository, the recycling of radionuclides would affect the uncontaminated water at this location. Because the 30-km location is downgradient of the compliance point, the recycled radionuclides cannot migrate to the 18-km compliance point. In this scenario, the irrigation recycling at 30 km would have no effect on the radionuclide concentrations in water withdrawn at the 18-km compliance point.

Scenario 3: Locally Grown Food Produced at the 18-km Compliance Point Using Well Water Withdrawn at that Location

In this scenario, locally grown food consumed by the receptor is assumed to be produced at the 18-km compliance point. All water used to produce this food is assumed to be withdrawn at the 18-km compliance location. Agriculture is assumed to occur in the immediate vicinity of the wells. This would be unlikely, because the fields would be in the flood zone of Fortymile Wash.

Under current conditions, the groundwater outflow from the Jackass Flats hydrographic basin (227-A), which includes Yucca Mountain and the point of compliance location, is 8,100 acre ft/year (EPA 1999 [DIRS 143799], p. 8-36). This indicates that approximately 37 percent (3,000 acre-ft/year / 8,100 acre-ft/year) of the water recaptured by receptor wells would be recycled water. This yields a “closed to open system” ratio of 1.5.

Scenario 4: Locally Grown Food Produced 18-km Downgradient From the Repository, Out of Fortymile Wash, Using Well Water Withdrawn at the 18-km Compliance Location

In this scenario, locally grown food consumed by the receptor is assumed to be produced at the 18-km compliance point. All water used to produce this food is assumed to be withdrawn at the 18-km compliance location. However, unlike Scenario 3, agriculture is assumed to occur out of Fortymile Wash such that flash flooding does not impact farming.

Well water would be used to irrigate crops some distance from the withdrawal point. This distance would further reduce the likelihood of recycling such that the “closed to open system” ratio would be substantially less than estimated for Scenario 3.

It is important to note that the steady-state contaminant concentrations due to recycling would require a significant period of continuous irrigation at one location with contaminated groundwater to develop. For groundwater advection in the unsaturated conditions of the alluvium below the irrigated field the advective velocity is defined as:

$$v = \frac{q_w}{\phi_T \cdot S_l}. \qquad \text{(Eq. 6-6)}$$

Where: q_w = The vertical groundwater flux (corresponding to the recharge rate due to over watering of the irrigated field).

S_l = The liquid saturation of the alluvium beneath the irrigated field.

ϕ_T = The total porosity of the alluvium.

The advective transport velocity of a nonsorbing radionuclide is estimated using representative values for these parameters. The recharge rate is taken from the average value of the overwatering rate for irrigated alfalfa farming as about 0.15 m/year (BSC 2003 [DIRS 169673], Table 6.9-1). The liquid saturation in the alluvium beneath the irrigated fields is estimated to be about 0.45 based on the average of measurements of gravimetric moisture content in cores from six wells in the Amargosa Farms area (Stonestrom et al. 2003 [DIRS 165862]). The average total porosity of alluvium is estimated to be about 0.30 (BSC 2005 [DIRS 174012], Section 6.5.2.14). The resulting estimate for the vertical advective velocity of groundwater in the UZ beneath the irrigated fields is 1.1 m/year.

The depth to the water table at the boundary of the accessible environment along the likely SZ flow path from the repository can be estimated from information at well NC-EWDP-19P, resulting in a depth of 111.7 m to the water table (DTN: GS010908312332.002 [DIRS 163555]). Using this depth and the estimated advective velocity, the transport time of a nonsorbing radionuclide from beneath an irrigated field to the water table would be approximately 100 years. This transport time would constitute one cycle of return flow to the pumping well, and numerous cycles would be required to attain the steady-state contaminant concentration in a recycling system. The expected transport time of a moderately sorbing radionuclide, such as ^{237}Np, beneath the irrigated field to the water table would be about 4,100 years, based on the median value of the sorption coefficient of 6.35 mL/g in alluvium (BSC 2005 [DIRS 174012], Table 7-1). The depth to the water table at the boundary of the accessible environment would be less under future wetter climatic conditions. The transport times of radionuclides from beneath an irrigated field to the water table is proportional to the depth of the water table, so transport times would also be less. However, water table rise at this location would be significantly less than the approximate maximum rise of 100 m at the repository (see Section 6.2.10), because of its location closer to potential groundwater discharge areas activated by glacial-transition climatic conditions in Amargosa Valley. Consequently, there still would be significantly long transport times from beneath an irrigated field to the water table for moderately to strongly sorbing radionuclides under future wetter climatic conditions.

Overall, this sensitivity analysis indicates that the impact of recycling of radionuclides by leaching from soils in irrigated fields would be small. Open system behavior resulting from non-agricultural uses of groundwater and noncapture of contaminated recharge by receptor wells would lead to only small increases in steady-state radionuclide concentrations in groundwater. In addition, the estimated transport times of radionuclides in the UZ beneath the irrigated fields would require relatively long time periods of continuous irrigation with contaminated groundwater for such steady-state conditions to be achieved. This conclusion provides additional support for the screening decision to exclude this FEP based on regulatory arguments.

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7. CONCLUSIONS

This analysis report evaluates and documents the inclusion or exclusion of the saturated zone (SZ) features, events, and processes (FEPs) with respect to modeling used to support the total system performance assessment (TSPA) for license application (LA) of a nuclear waste repository at Yucca Mountain, Nevada.

A screening decision, either *Included* or *Excluded,* is given for each FEP along with the technical basis for the decision. For included FEPs, this analysis summarizes the implementation of the FEP in TSPA-LA (i.e., how the FEP is included). For excluded FEPs, this analysis provides the technical basis for exclusion from TSPA-LA (i.e., why the FEP is excluded). The use and limitation of this analysis are discussed in Section 1.3. Uncertainties are not considered as part of the FEP evaluations. Uncertainty is only implicitly captured for included FEPs through the uncertainties associated with the direct inputs from the model reports.

The conclusions from this document (FEP Screening Decision, TSPA Disposition for included FEPs, or Screening Argument for excluded FEPs), along with any modifications to the FEP list, FEP names, and/or FEP descriptions, are incorporated in the Yucca Mountain TSPA-LA FEP database. The FEP database also contains Screening Decisions (Include or Exclude), Screening Arguments, and TSPA Dispositions quoted all other FEP reports. Table 7.1-1 summarizes the SZ FEP screening decisions.

Table 7.1-1. Summary of SZ FEPs Screening

Section Number	FEP Number	FEP Name	Screening Decision	Basis
6.2.1	1.2.02.01.0A	Fractures	Included	N/A
6.2.2	1.2.02.02.0A	Faults	Included	N/A
6.2.3	1.2.04.02.0A	Igneous activity changes rock properties	Excluded	Low Consequence
6.2.4	1.2.04.07.0B	Ash redistribution in groundwater	Excluded	Low Consequence
6.2.5	1.2.06.00.0A	Hydrothermal activity	Excluded	Low Consequence
6.2.6	1.2.09.02.0A	Large-scale dissolution	Excluded	Low Consequence
6.2.7	1.2.10.01.0A	Hydrologic response to seismic activity	Excluded	Low Consequence
6.2.8	1.2.10.02.0A	Hydrologic response to igneous activity	Excluded	Low Consequence
6.2.9	1.3.07.01.0A	Water table decline	Excluded	Low Consequence
6.2.10	1.3.07.02.0A	Water table rise affects SZ	Included	N/A
6.2.11	1.4.07.01.0A	Water management activities	Included	N/A
6.2.12	1.4.07.02.0A	Wells	Included	N/A
6.2.13	2.1.09.21.0B	Transport of particles larger than colloids in the SZ	Excluded	Low Consequence
6.2.14	2.2.03.01.0A	Stratigraphy	Included	N/A
6.2.15	2.2.03.02.0A	Rock properties of host rock and other units	Included	N/A
6.2.16	2.2.06.01.0A	Seismic activity changes porosity and permeability of rock	Excluded	Low Consequence

Section Number	FEP Number	FEP Name	Screening Decision	Basis
6.2.17	2.2.06.02.0A	Seismic activity changes porosity and permeability of faults	Excluded	Low Consequence
6.2.18	2.2.06.02.0B	Seismic activity changes porosity and permeability of fractures	Excluded	Low Consequence
6.2.19	2.2.07.12.0A	Saturated groundwater flow in the geosphere	Included	N/A
6.2.20	2.2.07.13.0A	Water-conducting features in the SZ	Included	N/A
6.2.21	2.2.07.14.0A	Chemically-induced density effects on groundwater flow	Excluded	Low Consequence
6.2.22	2.2.07.15.0A	Advection and dispersion in the SZ	Included	N/A
6.2.23	2.2.07.16.0A	Dilution of radionuclides in groundwater	Included	N/A
6.2.24	2.2.07.17.0A	Diffusion in the SZ	Included	N/A
6.2.25	2.2.08.01.0A	Chemical characteristics of groundwater in the SZ	Included	N/A
6.2.26	2.2.08.03.0A	Geochemical interactions and evolution in the SZ	Excluded	Low Consequence
6.2.27	2.2.08.06.0A	Complexation in the SZ	Included	N/A
6.2.28	2.2.08.07.0A	Radionuclide solubility limits in the SZ	Excluded	Low Consequence
6.2.29	2.2.08.08.0A	Matrix diffusion in the SZ	Included	N/A
6.2.30	2.2.08.09.0A	Sorption in the SZ	Included	N/A
6.2.31	2.2.08.10.0A	Colloidal transport in the SZ	Included	N/A
6.2.32	2.2.08.11.0A	Groundwater discharge to surface within the reference biosphere	Excluded	Low Consequence
6.2.33	2.2.09.01.0A	Microbial activity in the SZ	Excluded	Low Consequence
6.2.34	2.2.10.02.0A	Thermal convection cell develops in SZ	Excluded	Low Consequence
6.2.35	2.2.10.03.0A	Natural geothermal effects on flow in the SZ	Included	N/A
6.2.36	2.2.10.04.0A	Thermo-mechanical stresses alter characteristics of fractures near repository	Excluded	Low Consequence
6.2.37	2.2.10.04.0B	Thermo-mechanical stresses alter characteristics of faults near repository	Excluded	Low Consequence
6.2.38	2.2.10.05.0A	Thermo-mechanical stresses alter characteristics of rocks above and below the repository	Excluded	Low Consequences
6.2.39	2.2.10.08.0A	Thermo-chemical alteration in the SZ (solubility, speciation, phase changes, precipitation/dissolution)	Excluded	Low Consequences
6.2.40	2.2.10.13.0A	Repository-induced thermal effects on flow in the SZ	Excluded	Low Consequence
6.2.41	2.2.11.01.0A	Gas effects in the SZ	Excluded	Low Consequence
6.2.42	2.2.12.00.0B	Undetected features in the SZ	Included	N/A

Table 7.1-1. Summary of SZ FEPs Screening (Continued)

Section Number	FEP Number	FEP Name	Screening Decision	Basis
6.2.43	2.3.11.04.0A	Groundwater discharge to surface outside the reference biosphere	Excluded	By Regulation
6.2.44	3.1.01.01.0A	Radioactive decay and ingrowth	Included	N/A
6.2.45	3.2.07.01.0A	Isotopic dilution	Excluded	Low Consequence
6.2.46	1.4.07.03.0A	Recycling of accumulated radionuclides from soils to groundwater	Excluded	By Regulation

FEP = feature, event, and process; LP = License Position; N/A = not applicable; SZ = saturated zone

All FEP information, including the SZ FEPs considered in this report, will be submitted to Technical Data Management System by the Yucca Mountain FEP database team as a final LA FEP list represented by a DTN. Documentation of the FEP database is given in a separate report.

The output DTN: MO0507MWDREGSC.000 contains the analysis used to evaluate the peak temperature and stress at the water table as discussed in Appendix C of this report. This DTN is intended only to provide information on the analysis carried out for this report. These data are not intended to be used as a source of input for other analyses.

The PRD (Canori and Leitner 2003 [DIRS 166275]) documents and categorizes the regulatory requirements and other project requirements and provides a crosswalk to the various YMP organizations that are responsible for ensuring that the criteria have been addressed in the LA. The regulatory requirements include criteria relevant to performance assessment activities, in general, and to FEP-related activities as they pertain to performance assessment, in particular. Table 7.2-1 provides a crosswalk between the regulatory requirements, the PRD, and the acceptance criteria provided in the YMRP NUREG-1804 (NRC 2003 [DIRS 163274], Sections 2.2.1.2.1.3 and 2.2.1.2.2.3).

The cited YMRP criteria (NRC 2003 [DIRS 163274]) are provided in Table 7.1-2. The YMRP acceptance criteria for FEP screening echo the regulatory screening criteria of low probability and low consequence but also allow for exclusion of a FEP if the process is specifically excluded by regulations (see Section 4.2.3). The relevant YMRP acceptance criteria and how they are addressed for the SZ FEPs are shown in Table 7.1-2.

Table 7.1-2. Relevant YMRP Acceptance Criteria and the Saturated Zone FEPs AMR

YMRP Section	Acceptance Criterion	Description	How and where addressed
Scenario Analysis and Event Probability: Scenario Analysis (from Section 2.2.1.2.1.3 NUREG-1804 [DIRS 163274])	1. The Identification of a list of FEPs Is Adequate	(1) The Safety Analysis Report contains a complete list of FEPs related to the geologic setting or the degradation, deterioration, or alteration of engineered barriers (including those processes that would affect the performance of natural barriers), that have the potential to influence repository performance. The list is consistent with the site characterization data. Moreover, the comprehensive features, events, and processes list includes, but is not limited to, potentially disruptive events related to igneous activity (extrusive and intrusive); seismic shaking (high-frequency-low magnitude, and rare large-magnitude events); tectonic evolution (slip on existing faults and formation of new faults); climatic change (change to pluvial conditions); and criticality.	The list of saturated zone FEPs is presented in Section 1.2, and FEP descriptions are presented in Section 6.2. Description and origin of the saturated zone FEP list and descriptions are presented in Section 6.1.1.
	2. Screening of the Initial List of Features, Events, and Processes Is Appropriate	(1) The DOE has identified all FEPs related to either the geologic setting or to the degradation, deterioration, or alteration of engineered barriers (including those processes that would affect the performance of natural barriers) that have been excluded.	The excluded saturated zone FEPs are listed in Table 7-1.
		(2) The DOE has provided justification for those FEPs that have been excluded. An acceptable justification for excluding FEPs is that either the FEP is specifically excluded by regulation; probability of the FEP (generally an event) falls below the regulatory criterion; or omission of the FEP does not significantly change the magnitude and time of the resulting radiological exposures to the reasonably maximally exposed individual, or radionuclide releases to the accessible environment.	See the method and approach discussion provided in Section 6.1.2 and the individual justification (by regulation, low probability, low consequence) for excluding FEPs. The justification (basis) is also included in Table 7-1.
		(3) The DOE has provided an adequate technical basis for each FEP excluded from the performance assessment to support the conclusion that either the FEP is specifically excluded by regulation, the probability of the FEP falls below the regulatory criterion, or omission of the FEP does not significantly change the magnitude and time of the resulting radiological exposures to the reasonably maximally exposed individual, or radionuclide releases to the accessible environment.	The individual FEP screening decisions and supporting technical bases are discussed in Section 6.2.

Table 7.1-2. Relevant YMRP Acceptance Criteria and the Saturated Zone FEPs AMR (Continued)

YMRP Section	Acceptance Criterion	Description	How and where addressed
Scenario Analysis and Event Probability: Identification of Events with Probability Greater than 10^{-8} per Year (from Section 2.2.1.2.2.3 NUREG-1804 [DIRS 163274])	1. Events are Adequately Defined	(1) Events or event classes are defined without ambiguity and used consistently in probability models, such that probabilities for each event or event class are estimated separately.	See the FEP Description provided for each FEP in Section 6.2 and the cited supporting AMRs.
		(2) Probabilities of intrusive and extrusive igneous events are calculated separately. Definitions of faulting and earthquakes are derived from the historical record, paleoseismic studies, or geological analyses. Criticality events are calculated separately by location.	The individual FEP screening decisions and supporting technical bases are discussed in Section 6.2. Criticality events and issues are not part of the Saturated Zone class of FEPs
	2. Probability Estimates for Future Events Are Supported by Appropriate Technical Bases.	(1) Probabilities for future natural events have considered past patterns of the natural events in the Yucca Mountain region, considering the likely future conditions and interactions of the natural and engineered repository system. These probability estimates have specifically included igneous events, faulting and seismic events, and criticality events.	Future naturally occurring events are addressed in the subsections of Section 6.2 of this analysis report.
	5. Uncertainty in Event Probability is Adequately Evaluated	(1) Probability values appropriately reflect uncertainties. Specifically: a. The DOE provides a technical basis for probability values used, and the values account for the uncertainty in the probability estimates. b. The uncertainty for reported probability values adequately reflects the influence of parameter uncertainty on the range of model results (i.e., precision) and the model uncertainty, as it affects the timing and magnitude of past events (i.e., accuracy).	The technical basis and discussion of uncertainties used for exclusion of saturated zone FEPs are discussed in the subsections of Section 6.2 for the individual FEPs.

DOE = U.S. Department of Energy; FEP = feature, event, and process.

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8. INPUTS AND REFERENCES

The following is a list of the references cited in this document. Column 2 represents the unique six-digit numerical identifiers (the Document Input Reference System numbers), which are placed in the text following the reference callout (e.g., BSC 2004 [DIRS 166335]). The purpose of these numbers is to assist in locating a specific reference. Multiple sources by the same author (e.g., BSC 2004) are sorted alphabetically by title.

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10 CFR 63. 2005 Energy: Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada. ACC: MOL.20050405.0118. 173273

66 FR 32074. 40 CFR Part 197, Public Health and Environmental Radiation Protection Standards for Yucca Mountain, NV; Final Rule. Readily available. 155216

66 FR 55732. Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain, NV, Final Rule. 10 CFR Parts 2, 19, 20, 21, 30, 40, 51, 60, 61, 63, 70, 72, 73, and 75. ACC: MOL.20050324.0102; MOL.20050418.0124. 156671

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LP-SIII.2Q-BSC, Rev. 0. Qualification of Unqualified Data. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: DOC.20050119.0002

LP-SIII.9Q-BSC, Rev. 0 ICN 1. Scientific Analyses. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: DOC.20040920.0001.

LP-SI.11Q-BSC, Rev. 0, ICN 1. Software Management. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: DOC.20041005.0008.

8.3 SOURCE DATA, LISTED BY DATA TRACKING NUMBER

GS000808312312.007. Ground-Water Altitudes from Manual Depth-to-Water Measurements at Various Boreholes November 1998 through December 1999. Submittal date: 08/21/2000. 155270

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GS010908312332.002. Borehole Data from Water-Level Data Analysis for the Saturated Zone Site-Scale Flow and Transport Model. Submittal date: 10/02/2001. 163555

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GS011108312322.006. Field and Chemical Data Collected between 1/20/00 and 4/24/01 and Isotopic Data Collected between 12/11/98 and 11/6/00 from Wells in the Yucca Mountain Area, Nye County, Nevada. Submittal date: 11/20/2001. 162911

GS931100121347.007. Selected Ground-Water Data for Yucca Mountain Region, Southern Nevada and Eastern California, Through December 1992. Submittal date: 11/30/1993. 149611

LA0407DK831811.001. Physical Parameters of Basaltic Magma and Eruption Phenomena. Submittal date: 07/15/2004. 170768

MO0102DQRBTEMP.001. Temperature Data Collected from Boreholes Near Yucca Mountain in Early 1980's. Submittal date: 02/21/2001. 154733

MO0408MWDDDMIO.002. Drift Degradation Model Inputs and Outputs. Submittal date: 08/31/2004. 171483

MO0501MWDBDCFS.000. Biosphere Dose Conversion Factors for the Groundwater Exposure Scenario Calculated Using ICRP 72 Dose Coefficients. Submittal date: 01/26/2005. 172835

MO0501SEPFEPLA.001. LA FEP List and Screening. Submittal date: 01/17/2005. 172601

MO0504MWDNUMWP.001. Number of Waste Packages Hit by Igneous Intrusion. Submittal date: 04/22/2005. 173521

MO0012MAJIONIS.000. Water-Major Ion and Isotope Data. Submittal date: 12/01/2000. 153679

SN0310T0505503.004. Initial Radionuclide Inventories for TSPA-LA. Submittal date: 10/27/2003. 168761

8.4 SOFTWARE CODES

BSC (Bechtel SAIC Company) 2002. Software Code: FLAC3D. V2.1. PC WINDOWS 2000/NT 4.0. 10502-2.1-00. 161947

LANL (Los Alamos National Laboratory) 2003. *Software Code: FEHM.* V2.20. SUN, PC. 10086-2.20-00. 161725

SNL (Sandia National Laboratories) 2003. *Software Code: SZ_Convolute.* V2.2. PC, Windows 2000. 10207-2.2-00. 163344

8.5 OUTPUT DATA, LISTED BY DATA TRACKING NUMBER

MO0507MWDREGSC.000 SUPPLEMENTARY OUTPUT DATA FROM THE REGIONAL SCALE THERMAL-MECHANICAL ANALYSIS. Submittal date: 07/28/2005.

APPENDIX A

QUALIFICATION OF UNQUALIFIED DATA

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A1. QUALIFICATION OF ANALYSIS FROM PALEO-SPRING DEPOSITS IN THE NORTHERN AMARGOSA DESERT

Some analyses used as direct input were obtained from outside sources. These data are demonstrated in this appendix to be suitable for use within this report, in accordance with LP-SIII.2Q-BSC, *Qualification of Unqualified Data*, and LP-SIII.9Q-BSC, *Scientific Analyses*.

A1.1 DATA FOR QUALIFICATION

Summary of Discharge Deposits in the Amargosa Valley (Paces et al. 1997 [DIRS 109148]) was prepared by the Environmental Science Team, Earth Science Investigations Program, YMP Branch, Water Resources Division of USGS regarding activities conducted in association with Milestone SPC333M4, "Evaluation of Paleo Ground-Water Discharge" (DOE 1997 [DIRS 171970]). This USGS report analyzes age, isotope, and paleontological data and summarizes the current understanding and implications of paleo-spring deposits located in the Amargosa Valley area.

The USGS report (Paces et al. 1997 [DIRS 109148]) is cited as direct input in this analysis report to exclude FEP 2.2.08.11.0A, Groundwater Discharge to Surface Within the Reference Biosphere on the basis of low consequence.

A1.2 QUALIFICATION METHOD AND RATIONALE FOR SELECTION

The data qualification was performed in accordance with the data qualification plan (Figure A-1), developed according to LP-SIII.2Q-BSC. The Equivalent QA Program method, described in Attachment 3 of LP-SIII.2Q Rev.0, was selected for use. This method was chosen, because the YMP Branch of the USGS has worked in cooperation with the YMP Management and Operating Contractor for many years, and USGS Milestone SPC333M4, (USGS 1997 [DIRS 171970]) activities underwent a DOE Office of Quality Assurance (OQA) surveillance in late 1997. The objective of the surveillance was to verify compliance with USGS technical and implementing procedures in the production of the milestone.

BSC	**Data Qualification Plan** *Complete only applicable items.*	QA: QA Page 1 of 1

Section I. Organizational Information

Qualification Title

Qualification of Analysis from Paleo-Spring deposits in the Northern Amargosa Desert

Requesting Organization

BSC Post Closure Activities – Natural Systems Team

Section II. Process Planning Requirements

1. List of Unqualified Data to be Evaluated

Paces, J. B.; Whelan, J. F.; Forester, R. M.; Bradbury, J. P.; Marshall, B. D.; and Mahen, S. A. 1997. Summary of Discharge Deposits in the Amargos Valley. Milestone SPC333M4. Denver, Colorado: U.S. Geological Survey. ACC: MOL.19981104.0151. [DIRS 109148]

2. Type of Data Qualification Method(s) [Including rationale for selection of method(s) (Attachment 3) and qualification attributes (Attachment 4)]

Equivalent QA program shall be the qualification method used. The USGS has a QA program similar in scope and implementation to the general process requirements of the QARD. Qualification attributes to be examined may include items 1, 2, 5, 6, 8 and /or 11 from attachment 4 of LP-SIII.2Q-BSC Rev 00 ICN 00 *Qualification of Unqualified Data.*

3. Data Qualification Team and Additional Support Staff Required DG 8/18/05

Stephanie Kuzio, (chair), Carl Axness (checker) and ~~Jeff~~ James Graff (BSC-QA)

4. Data Evaluation Criteria

Evaluate and document that USGS QA program was similar in scope and implementation to the general process requirements of the QARD. The employed program must demonstrate industry acceptable scientific and administrative practices or processes.

5. Identification of Procedures Used

LP-SIII.2Q-BSC Rev 00 ICN 00 *Qualification of Unqualified Data.*
LP-SIII.9Q-BSC Rev 00 ICN 01 *Scientific Analysis*

Section III. Approval

Qualification Chairperson Printed Name	Qualification Chairperson Signature	Date
Stephanie Kuzio		8/12/2005
Responsible Manager Printed Name	**Responsible Manager Signature**	**Date**
Ming Zhu For Paul R. Dixon		8-14-05

LP-SIII.2Q-BSC FORM NO. LSIII2-1 (Rev. 01/19/2005)

Figure A-1. Qualification of Analysis from Paleo-Spring Deposits in the Northern Amargosa Desert

A1.3 EVALUATION CRITERIA

The evaluation criteria are based on the requirements in Attachment 3 and the applicable qualification attributes listed in Attachment 4 of LP-SIII.2Q-BSC. Use of qualification Method 1, Equivalent QA Program, requires that an initial evaluation of the data quality and correctness be made by comparing the methods used to plan, collect, and analyze the data against generally accepted scientific or engineering practices. If this comparison is adequate, then the acquisition, development, or processing of data must be demonstrated to be functionally equivalent (i.e., similar in scope and implementation) to the general process requirements of the *Quality Assurance Requirements and Description* (QARD) (DOE 2004 [DIRS 171539]). A condition of this method is that the qualification team assess the functional equivalence of the data-gathering process to applicable QARD (DOE 2004 [DIRS 171539] concepts, as identified by the attributes in LP-SIII.2Q-BSC, Attachment 4 (e.g., Attributes 1, 2, 5, 6, 8, and/or 11). These attributes are listed here:

- **Qualification Attribute 1**—Qualifications of personnel or organizations generating the data are comparable to qualification requirements of personnel generating similar data under approved 10 CFR 60, Subpart G, program.
- **Qualification Attribute 2—**The technical adequacy of equipment and procedures used to collect and analyze the data.
- **Qualification Attribute 5**—The quality and reliability of the measurement control program under which the data were generated.
- **Qualification Attribute 6**—The extent to which conditions under which the data were generated may partially meet 10 CFR 60, Subpart G.
- **Qualification Attribute 8**—Prior peer or other professional reviews of the data and their results.
- **Qualification Attribute 11**—The degree to which independent audits of the process that generated the data were conducted.

A1.4 EVALUATION RESULTS

In the initial evaluation of data quality and correctness, Paces et al. (1997 [DIRS 109148]) analyze the new age, isotope, and paleontological data and present an interpretive evaluation on past discharge activity in the northern Amargosa Valley. Thermoluminescence data, stable isotope data (O and C), other isotope data (strontium and uranium-series disequilibrium), as well as diatom and ostracode (paleontological) data, are generally accepted by the scientific (geologic and hydrologic) community for use in determining age, temperature, climatic, and environmental conditions of paleo flowing springs. Standard geologic field practices were used for sampling from trench wall and natural outcrops, mass spectrometry was used in collecting isotopic data, and thermoluminescence data were collected by a commonly accepted technique. A list of all procedures used for this activity are found in OQA surveillance record No. USGS-SR-97-061 (DOE 1997 [DIRS 171970], Item 8). These technical procedures are all USGS approved. The data quality and correctness are determined to be adequate for the implementation of the Equivalent QA Program qualification method.

OQA Surveillance No. USGS-SR-97-061 (DOE 1997 [DIRS 171970]) was conducted to verify compliance with USGS procedures in the preparation of memorandum report Milestone SPC333M4, "Evaluation of Paleo Ground-Water Discharge," September 23 through October 3, 1997. The conclusion of the surveillance was that the USGS has adequately implemented the QA program as it applied to the activities conducted in association with Milestone SPC333M4. No deficiency documents were issued as a result of this surveillance.

The results of assessment of the functional equivalence of the data-gathering process to applicable QARD (DOE 2004 [DIRS 171539]) concepts, as identified by the attributes in Attachment 4, LP-SIII.2Q-BSC, are the following:

- **Qualification Attribute 1**—Surveillance record No. USGS-SR-97-061 (DOE 1997 [DIRS 171970]), Items 1 and 2, and Attachment 1 indicate that the qualification of personnel generating the data are comparable to those qualifications approved by the 10 CFR 60, Subpart G [DIRS 173273] program.

- **Qualification Attribute 2**—Items 3, 4, 8, and 10 of the surveillance record (DOE 1997 [DIRS 171970]) demonstrate the technical adequacy of equipment and procedures used to collect and analyze the data.

- **Qualification Attribute 5**—Items 3, 4, 5, 6, 7, 8, and 10 of the surveillance record (DOE 1997 [DIRS 171970]) demonstrate the quality and reliability of the measurement control program under which the data were generated.

- **Qualification Attribute 6**—The surveillance record determined that the USGS has adequately implemented a QA program as it applies to activities associated with Milestone SPC333M4 (DOE 1997 [DIRS 171970]). This conclusion was based on objective evidence and discussions with USGS personnel. There were no deficiency documents issued as a result of the surveillance. The conditions under which the data were generated partially meet 10 CFR 60, Subpart G [DIRS 173273].

- **Qualification Attribute 8**—Item 11 of the surveillance record (DOE 1997 [DIRS 171970]) demonstrates that technical reviews were done before the data packages were sent to the YMP. Dr. Zell Peterman, Chief of the USGS YMPB Environmental Science Team, conducted a management review.

- **Qualification Attribute 11**—There were no independent audits conducted in association with the data generation process.

A1.5 EVALUATION RECOMMENDATION

The evaluation found that the USGS report (Paces et al. 1997 [DIRS 109148]) analyses data were adequate for the implementation of the Equivalent QA Program qualification method. The Equivalent QA Program method was used to determine that qualification Attributes 1, 2, 5, 6, and 8 (Attachment 4, LP-SIII.2Q-BSC) were satisfied by the USGS QA program. The USGS QA program was found to be the functional equivalent to the general processes required by the QARD (DOE 2004 [DIRS 171539]). Consequently, it is recommended that the USGS report be qualified for use as direct input within this analysis report.

A2. JUSTIFICATION OF DATA FROM OUTSIDE SOURCES

The following information is being provided to justify that these data are suitable for the intended use and are qualified for use in this report.

A2.1 JUSTIFICATION FOR USING DATA FROM JOURNAL ARTICLE

"Paleoclimatic Inferences from a 120,000-year Calcite Record of Water-Table Fluctuation in Browns Room of Devils Hole, Nevada" (Szabo et al. 1994 [DIRS 100088]) is a professional journal article. It provides information on the magnitude and timing of cyclic changes in water table elevation in the Yucca Mountain region due to climate change. Submissions to *Quaternary Research* undergo a peer review before acceptance. The authors are part of a US Geological Survey team that has studied the evidence for the nature and timing of climate change at Devils Hole for several years. This work has resulted in several publications describing the results of the work that provide a chronology of climate change over the past 500,000 years. The work has been generally accepted by the scientific community and is a major source for most climate reconstructions in the region and the world (for example, see the climate discussions in ANL-NBS-GS-000008 [DIRS 170002]). The radiometric and stable isotope data used in this article were collected in US Government laboratories using state of the art equipment and techniques. The data were rigorously checked for accuracy and the stable isotopic data were rerun a second time at a later date to assure reproducibility. Appropriate standards were used in the respective laboratories. Because the interpretation of the timing of climatic change derived from the Devils Hole work differed from conventional thinking about the causes and timing of climate change at the time the first publications were produced, the assumptions and methods used in this article were reviewed and evaluated extensively not only by the USGS and for presentation in peer-reviewed journals, but by extensive discussion in the open literature. The data have withstood this detailed scrutiny and are considered accurate by conventional standard for these types of measurements.

The petrographic and morphologic differences between calcite precipitated below, at, or above the present water table and uranium-series dating were used to reconstruct a chronology of water-table fluctuation for the past 120,000 years in Browns Room. This location is a subterranean air-filled chamber of Devils Hole fissure adjacent to the discharge area of the large Ash Meadows groundwater flow system in southern Nevada. The chronology of water-table fluctuation permits the following interpretations:

- Past climate fluctuations are cyclical and are propagated through the unsaturated zone to saturated zone.
- Calcite crystal formation is a function of degree of saturation.

- Evidence of past water table elevations is seen in crystal morphology and growth in Browns Room.
- Crystal morphology in Browns Room indicates the water table dropped by at least 6 m between 53,000 and 92,000 years ago.
- The current climate represents an extremely arid condition.

For the reasons stated above, this information is considered to be reliable sources and appropriate for intended use.

A2.2 JUSTIFICATION FOR USING DATA FROM HYDROLOGY TEXTBOOK

Groundwater (Freeze and Cherry 1979 [DIRS 101173]) is a hydrology textbook. Technical information presented in the textbook and used in this report includes (1) carbonate and halite solubilities, which are important in describing how volcanic rocks tend to weather to clay minerals with a relatively small amount of silica going into solution, and (2) the equation for retardation factor for flow in the saturated zone. The technical information in the book has undergone peer review before publication. This book is designed for use as a text in introductory groundwater courses and has been widely used in college courses since its initial publication and is still in print. Item 1 and 2 above are considered to be reasonable for the intended use in this report and are justified in following two paragraphs.Dr. R. Allen Freeze taught at the University of British Columbia for 18 years where he served as Director of the Geological Engineering Program and Associate Dean of Graduate Studies. Dr. Freeze has published more than 100 papers and has received the Horton and Macelwane awards from the American Geophysical Union, the Meizner Award from the Geological Society of America, and the Theis Award from the American Institute of Hydrology. He is the former editor of the journal *Water Resources Research*, and is the former president of the Hydrology Section of the American Geophysical Union. Dr. Freeze has also served as an expert for the Yucca Mountain saturated zone expert elicitation project.

Dr. John A. Cherry has been a professor at the University of Waterloo since 1971. He has a Ph.D. in hydrogeology. Dr. Cherry's research for the past twenty-five years has focused on field studies of groundwater contamination, including the integration of field information with laboratory and modeling studies for assessment of site contamination and remedial options. From 1981-1987 he was Director of Waterloo's Institute for Groundwater Research. For his contributions to knowledge on groundwater contamination, Dr. Cherry has received awards from the American Geophysical Union, the Geological Society of America, the National Ground Water Association and the Ontario government.

A2.3 JUSTIFICATION FOR USING DATA FROM FUNDAMENTALS OF SOIL PHYSICS TEXTBOOK

Fundamentals of Soil Physics (Hillel, D. 1980 [DIRS 101134]) is a soil physics textbook. Information in the book has undergone extensive peer review before publication. This book is designed for use as a text in soil physics courses of the type normally taught to the upper-level and undergraduate students in the soil physics and agricultural and environmental and engineering science. Because of its coverage of the fundamental principles governing soil physics this book can also be used by professionals involved in the related disciplines. This publication can be considered a reference source. Information from this book used in this analysis report is an equation for the estimation of the settling velocity of particles slightly larger than a colloid using Stokes' Law (Section 6.2.13). Therefore this equation is considered to be from a reliable source and appropriate for intended use.

A2.4 JUSTIFICATION FOR USING DATA FROM PHYSICAL AND CHEMICAL HYDROGEOLOGY TEXTBOOK

Physical and Chemical Hydrogeology (Domenico, P.A. and Schwartz, F.W. 1990. [DIRS 100569]) is a hydrogeology textbook. Information in this book has undergone peer review before publication. This book is designed for use as a text in introductory groundwater courses of the type normally taught in the junior or senior year of college undergraduate physical sciences. This comprehensive volume not only covers all major areas of hydrogeology, it takes a process-oriented, integrated approach so that readers can gain a complete understanding of the relationship between physical and chemical aspects of this subject. It also provides a good balance between theory and application and includes new areas such as contaminant hydrogeology. This textbook is designed to serve a diversity of interests, including those of geologists, practicing hydrogeologists and engineers, geochemists, and geophysicists interested in fluid dynamics. Equation for radioactive decay, Darcy's Law written in terms of hydraulic gradient and hydraulic conductivity and pressure gradient and permeability and equation for advective velocity are presented in the textbook and used in this report to calculate radioactive decay during transport through the UZ (Section 6.2.4) and to compute pore velocity and specific discharge (Section 6.2.13). This information is considered to be from a reliable source and appropriate for intended use.

A2.5 JUSTIFICATION FOR USING DATA FROM HEALTH PHYSICS TEXTBOOK

Introduction to Health Physics (Cember 1983 [DIRS 108074]) is a textbook used for an upper division undergraduate or first graduate course in radiological protection, health physics, or radiation safety. It provides students with a basic understanding of the biophysical bases of radiation, radiation safety standards, and the key factors in radiation protection. It also includes computer use in dose calculation and dose limit recommendations. Emphasizes a problem-solving approach that will serve students into their clinical careers. This is a classic textbook that has been used to train countless professionals in the fundamentals of radiation protection and safety. The information from this textbook used in this analysis concerns fundamental principles of the radioactive decay kinetics. This information was used in Section 6.2.4 to convert mass-based to activity-based quantities of radionucldies. Therefore this equation is considered to be from a reliable source and appropriate for intended use.

A2.6 JUSTIFICATION FOR USING DATA FROM NATIONAL RESEARCH COUNCIL REPORT

The National Research Council (1992 [DIRS 105162]) reference provides the basis for regional extensional rates declining from a peak of 10-30 mm/year, 10-12 ma, to 5-10 mm/year 5 ma and are in a declining state today. The reference also predicts a rise in water table given future seismic events. Numerical results using a seismic dislocation model indicate the maximum rise would be approximately 10 m.

A2.6.1 Extent to which the Data Demonstrate the Properties of Interest

Seismic dislocation and water-level changes are discussed in a report prepared by the Panel on Coupled Hydrologic/Tectonic/Hydrothermal Systems at Yucca Mountain, commissioned by the National Research Council. The panel reviewed an alternative conceptual model that predicted large changes in groundwater level, and concluded that the model was infeasible. The panel stated that seismic dislocation would at most elevate the water levels a few tens of meters (National Research Council 1992 [DIRS 105162]), page 7).

A2.6.2 Reliability of Data Source

The project that is the subject of this report was approved by the governing board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competencies and with regard for appropriate balance. This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

PANEL ON COUPLED PROCESSES AT YUCCA MOUNTAIN:

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GEORGE A. THOMPSON, Stanford University, Vice-Chairman
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A2.7 JUSTIFICATION FOR USING DATA FROM UNITED STATES GEOLOGICAL SOCIETY REPORT

The data on displacement of Solitario Canyon fault at Enhanced Characterization of the Repository Block (ECRB) Cross drift were taken from the report titled *Geology of the ECRB Cross Drift – Exploratory Studies Facility, Yucca Mountain Project, Yucca Mountain, Nevada* authored by Mongano, G.S.; Singleton, W.L.; Moyer, T.C.; Beason, S.C.; Eatman, G.L.W.; Albin, A.L.; and Lung, R.C. (Mongano et al. 1999 [DIRS 149850]). The report was jointly written by the U.S. Bureau of Reclamation (USBR) and U.S. Geological Survey (USGS) and prepared in cooperation with the Nevada Field Office, U.S. Department of Energy.

The USGS was created by an act of Congress in 1879, and is the sole science agency for the Department of the Interior. The primary assets of the USGS are its natural science expertise and its vast earth and biological data holdings. The USGS provides scientific information related to water management, biological, energy, and mineral resources. USBR is a water management agency whose mission is to manage, develop, and protect water and related resources.

The subject report summarizes the U.S. Bureau of Reclamation’s mapping of the stratigraphy and structure of the ECRB Cross Drift. It also includes statistical analyses of fractures and the geotechnical and engineering characteristics of the rocks. All the data used in the development of that report were collected and the report was prepared in accordance with approved YMP-USGS quality assurance procedures implementing requirements of the QARD. The report was produced by the team of scientists and is considered technically defensible.

The data in the report includes the value of the Solitario Canyon Fault's cumulative displacement, which is compared in the analysis of SZ FEPs (Sections 6.2.16, 6.2.17, 6.2.18) to an estimated displacement of the fault. This comparison is an order of magnitude comparison used to show that the hydrologic properties will remain essentially unchanged given the relatively small change in displacement of the fault. These data provide an appropriate technical basis for the screening arguments and are considered qualified for intended use.

APPENDIX B

DERIVATION OF THE CLOSED (WITH LOSSES) TO OPEN SYSTEM RECEPTOR WELL CONCENTRATION RATIO

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B1. DERIVATION OF THE CLOSED (WITH LOSSES) TO OPEN SYSTEM RECEPTOR WELL CONCENTRATION RATIO

A control volume that contains the entire receptor well–biosphere system is defined to determine the time-dependent contaminant mass within the volume. This control volume assumes that contaminated water used for irrigation is recycled back to the well. Boundary conditions are (1) the introduction of contaminant from the saturated zone, (2) the removal of contaminant from the system through the use of groundwater for purposes other than irrigation, and (3) any recycled contaminant that is not captured by the receptor wells. The inherent assumption is that the entire contaminant plume arriving from the saturated zone is intercepted by the receptor wells. This control volume is shown schematically below.

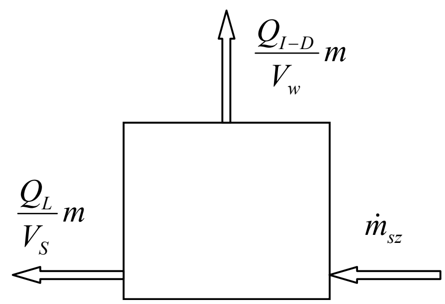

Figure B-1. Diagram of the Control Volume for Radionuclide Recycling

The differential equation that describes the change in contaminant mass within the control volume as a function of time is given by Equation B-1:

$$\frac{\mathrm{d}m}{\mathrm{d}t} = \dot{m}_{sz} - m\left(\frac{Q_{I-D}}{V_w} + \frac{Q_L}{V_s}\right) \qquad \text{(Eq. B-1)}$$

where:

m	=	mass of contaminant in the control volume (kg)
$\dot{m}_{sz}$	=	mass flux of contaminant entering the control volume from the saturated zone (kg/year)
Q_{I-D}	=	amount of water used annually for purposes other than irrigation (acre-ft/year)
Q_L	=	amount of contaminated recycled water annually lost from the system (amount that is not captured by the receptor wells) (acre-ft/year)
V_w	=	volume of the well (m^3)
V_s	=	volume of the soil that contaminated water is used to irrigate (m^3)

This equation becomes:

$$\frac{\mathrm{d}m}{\mathrm{d}t} + Zm = \dot{m}_{sz}$$
$$\text{Where: } \quad Z = \left(\frac{Q_{I-D}}{V_w} + \frac{Q_L}{V_s} \right) \tag{Eq. B-2}$$

This is a linear, first-order differential equation that takes on the following solution:

$$\mathrm{m}\,\mathrm{e}^{\int Zdt} = \dot{m}_{sz} \int \mathrm{e}^{\int Zdt} dt + C \tag{Eq. B-3}$$

Which becomes:

$$m = \frac{\dot{m}_{sz}}{Z} + Ce^{-Zt}$$
$$\text{Where: } \quad Z = \left(\frac{Q_{I-D}}{V_w} + \frac{Q_L}{V_s} \right) \tag{Eq. B-4}$$

or:

$$m = \frac{\dot{m}_{sz}}{\left(\frac{Q_{I-D}}{V_w} + \frac{Q_L}{V_s} \right)} + Ce^{-\left(\frac{Q_{I-D}}{V_w} + \frac{Q_L}{V_s} \right)t} \tag{Eq. B-5}$$

Initially, the mass in the control volume is equal to zero, which results in:

$$C = -\frac{\dot{m}_{sz}}{\left(\frac{Q_{I-D}}{V_w} + \frac{Q_L}{V_s} \right)} \tag{Eq. B-6}$$

Thus, the equation that defines the time-dependent mass in the control volume becomes:

$$m = \frac{\dot{m}_{sz}}{\left(\frac{Q_{I-D}}{V_w} + \frac{Q_L}{V_s} \right)} - \frac{\dot{m}_{sz}}{\left(\frac{Q_{I-D}}{V_w} + \frac{Q_L}{V_s} \right)} e^{-\left(\frac{Q_{I-D}}{V_w} + \frac{Q_L}{V_s} \right)t} \tag{Eq. B-7}$$

or:

$$m = \frac{\dot{m}_{sz}}{\left(\frac{Q_{I-D}}{V_w} + \frac{Q_L}{V_s}\right)} \left[1 - e^{-\left(\frac{Q_{I-D}}{V_w} + \frac{Q_L}{V_s}\right)t} \right] \qquad \text{(Eq. B-8)}$$

The purpose in developing this equation is not to explicitly calculate the time-dependent mass of contaminant in the control volume. Rather, this equation shows that losses will ultimately cause the system to arrive at steady-state conditions.

The overall control volume above is next divided into two control volumes: one for the receptor "wells" and one for the surface soil. These control volumes and the in-flows and out-flows from each are shown below. Note that the transfer of contaminant along other transport pathways in the biosphere is ignored.

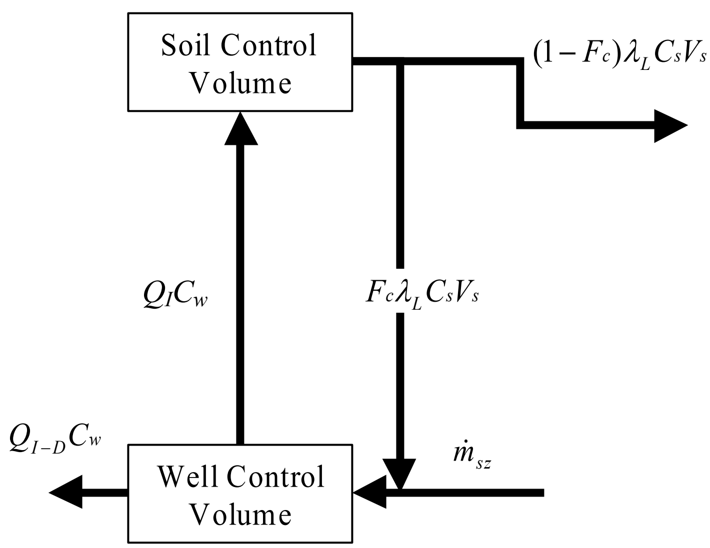

Figure B-2. Diagram of the Control Volumes for Receptor Wells and Surface Soils

Two coupled differential equations define the rate of change of contaminant mass within each of the control volumes.

$$\begin{aligned} &\text{WELL:} \quad \frac{dm_w}{dt} = \dot{m}_{sz} + F_c \lambda_L C_s V_s - Q_I C_w - Q_{I-D} C_w \\ &\text{SOIL:} \quad \frac{dm_s}{dt} = Q_I C_w - \lambda_L C_s V_s \end{aligned} \qquad \text{(Eq. B-9)}$$

Where:

m_w	=	mass of contaminant in the well control volume (kg)
m_s	=	mass of contaminant in the soil control volume (kg)

C_w	=	concentration of contaminant in the well (kg/m^3)
C_s	=	concentration of contaminant in the soil (kg-contaminant/kg-soil)
$\dot{m}_{sz}$	=	mass flux of contaminant entering the control volume from the saturated zone (kg/year)
V_w	=	volume of the well in the control volume (m^3)
V_s	=	volume of the surface soil in the control volume (m^3)
Q_{I-D}	=	amount of water used annually for purposes other than irrigation (acre-ft/year)
Q_I	=	amount of recycled water used annually for irrigation (acre-ft/year)
λ_L	=	leach rate of contaminant from the soil (year^{-1})
F_c	=	the fraction of recycled water that is recaptured by the wells.

The derivation above demonstrates that ultimately, the entire system will reach a steady state condition. As such, the two control volume system will also reach a steady state, and both of the time derivatives in the differential equations can be set to zero. This results in the following relation (from the soil equation):

$$C_s V_s = \frac{Q_I C_w}{\lambda_L} \qquad \text{(Eq. B-10)}$$

and (from the well equation):

$$\dot{m}_{sz} + F_c \lambda_L \frac{Q_I C_w}{\lambda_L} - Q_I C_w - Q_{I-D} C_w = 0 \qquad \text{(Eq. B-11)}$$

This becomes:

$$\dot{m}_{sz} + \left[F_c Q_I - Q_I - Q_{I-D} \right] C_w = 0 \qquad \text{(Eq. B-12)}$$

Solving for C_w gives:

$$C_w = \frac{\dot{m}_{sz}}{Q_{I-D} + Q_I - F_c Q_I} \qquad \text{(Eq. B-13)}$$

The total amount of water withdrawn, Q_T equals Q_{I-D} + Q_I. The amount of water used for irrigation is also a fraction of the total amount of water withdrawn, giving Q_I equal to F_i Q_T. So, the steady state concentration of contaminant in the well assuming a portion of the contaminant mass is recycled from the soil to the water table becomes:

$$C_w = \frac{\dot{m}_{sz}}{Q_T - F_c F_i Q_T} = \frac{\dot{m}_{sz}}{Q_T \left[1 - F_c F_i \right]} \qquad \text{(Eq. B-14)}$$

The “open-system” concentration of contaminant in the well is defined as the well concentration assuming no recycling of contaminant. This is given as:

$$C_{w-O} = \frac{\dot{m}_{sz}}{Q_T} \qquad \text{(Eq. B-15)}$$

So, the maximum increase in the contaminant concentration in the well as a result of recycling is given by the following:

$$\frac{C_w}{C_{w-O}} = \frac{\dfrac{\dot{m}_{sz}}{Q_T\left[1 - F_c\, F_i\right]}}{\dfrac{\dot{m}_{sz}}{Q_T}} = \frac{1}{\left[1 - F_c\, F_i\right]} \qquad \text{(Eq. B-16)}$$

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APPENDIX C

CALCULATION OF HEAT TRANSFER AND ESTIMATION OF THE THERMALLY INDUCED STRESS AT THE WATER TABLE

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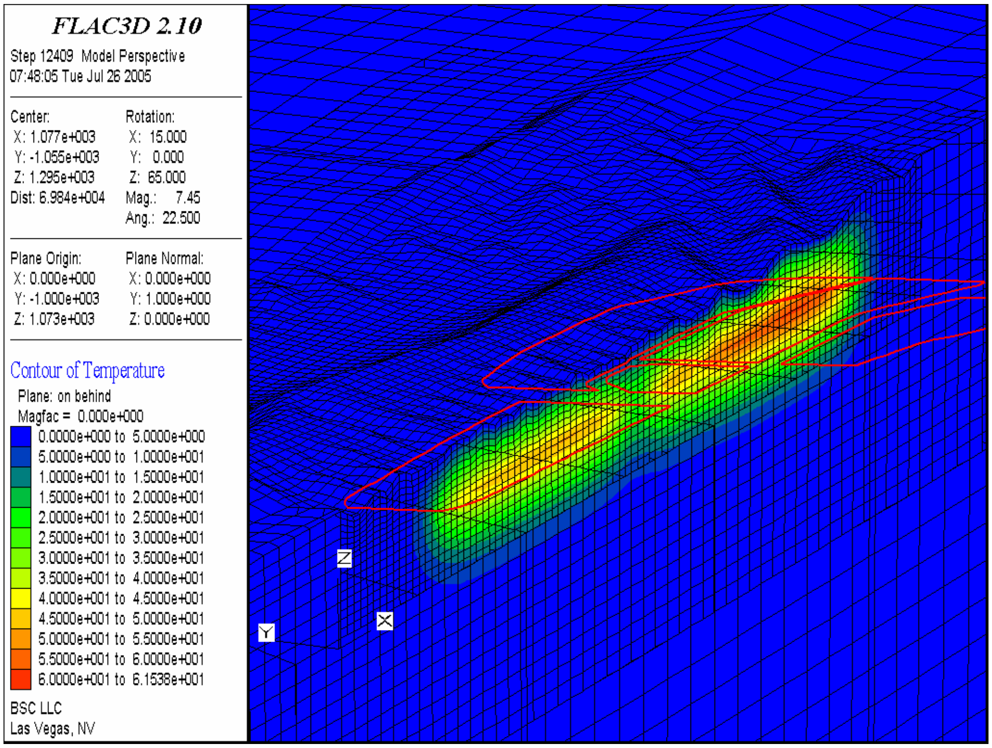
The purpose of this analysis is to estimate the potential changes in temperature and thermally induced stress at the water table due to the repository emplacement.

A three-dimensional regional scale thermal-mechanical analysis was conducted in Drift Degradation Analysis (BSC 2004 [DIRS 166107], Appendix C). The regional scale thermal-mechanical calculation included general topography and stratigraphy of the proposed Yucca Mountain site (BSC 2004 [DIRS 166107], Figure C-1). The calculation was conducted using the finite difference code FLAC3D (STN: 10502-2.1-00, BSC 2002 [DIRS 161947]).

Details of the calculation including thermal and mechanical properties of the rock masses were presented in Appendix C.2 of Drift Degradation Analysis (BSC 2004 [DIRS 166107]). The thermal conduction into the rock mass was considered in the analysis in order to compute the thermal stresses around the drifts. All the input files for the three-dimensional regional scale thermal-mechanical analysis are from output DTN: MO0408MWDDDMIO.002 ([DIRS 171483], NUFT Inputs FLAC 3D Inputs & Outputs\TM model\Part_#1_Grid_Thermal and Part_#2_Mechanical). The data files from the DTN were qualified within *Drift Degradation Analysis* (BSC 2004 [DIRS 166107], Table 4-1 and Appendix C.2). Using this qualified output, the three-dimensional thermal-mechanical analysis was repeated without any changes in the input data or modifications in the input files. Details of the input data and assumption for the three-dimensional thermal-mechanical analysis were presented in *Drift Degradation Analysis* (BSC 2004 [DIRS 166107], Table 4-1, Sections 5.1, and Appendix C.2).

Temperature change history and thermally induced stress at the water table due to the emplacement of the waste packages were estimated from the results of the three-dimensional thermal-mechanical calculation. The ambient temperature at the water table used in this calculation is 34ºC. Figures C-11 and C-12 of (BSC 2004 [DIRS 166107]) demonstrated the contour plots of the temperature increase after the 10, 100, 1000, and 10000 years of the emplacement (MO0408MWDDDMIO.002 [DIRS 171483]). Additional plots of the temperature change history are presented in Figures C-1, C-2, C-3, C-4 and C-5 (of this report) for 2000, 3,000, 4,000, 5,000, and 7,500 years of the emplacement respectively. At 4,000 years the estimate for maximum temperature occurs at the water table due to repository heating is about 60°C based upon an ambient temperature of 34°C. Although the three-dimensional model set the water table at 400 m below the repository the peak temperature of 60°C is from a depth below the repository of 300 m. This depth is representative of the water table location based on elevations of the approximate center of the northern panel from 800-IED-WIS0-00101-00-00A (BSC 2004 [DIRS 172801]) and the water level elevation of the closest well to this area, USW G-1 (BSC 2004 DIRS 170009], Table A-1). Although ambient groundwater flow will convect heat away from the area below the repository, it is assumed that the groundwater near the water table is stagnant and that none of the heat is swept downgradient by flow in the SZ. Consequently, the three-dimensional heat conduction model overestimates the values of temperature at and below the water table.

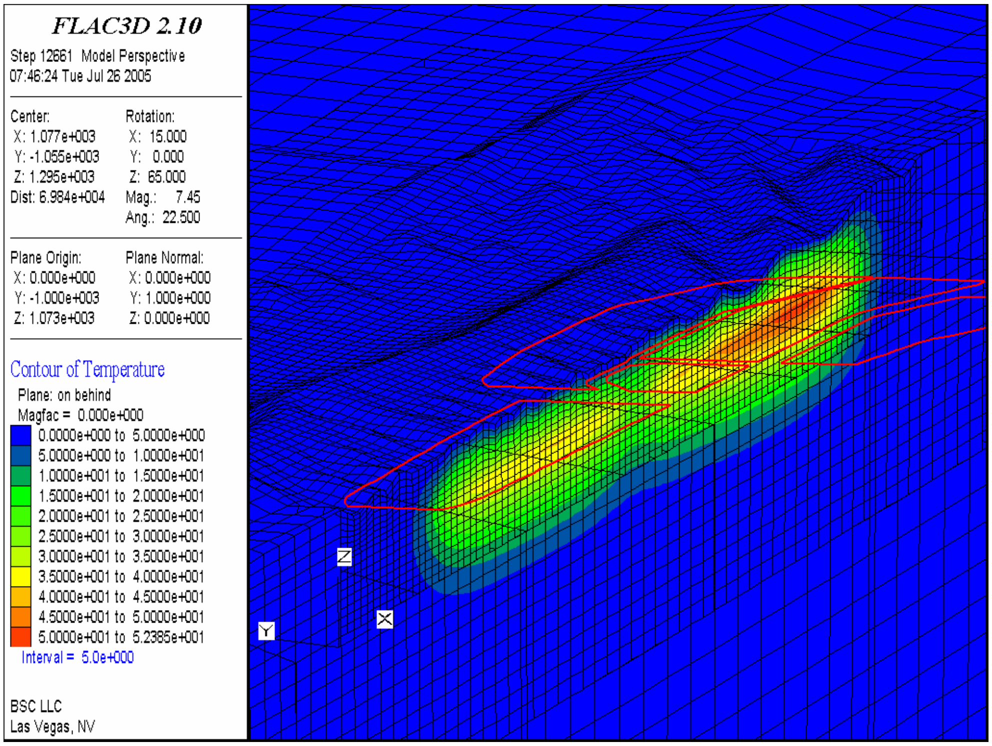
The thermally induced stresses at the 0 and 4000 years after the emplacement were presented in Figures C-6 and C-7, respectively. The resulting figures show that the thermally induced stress increases approximately 1.5 MPa at the 4000 years which corresponds to the peak at the water table. The results conclude that thermal-mechanical stresses at the water table are not enough to produce a compressional stress that would significantly affect fracture permeability in the SZ.



Output DTN: MO0507MWDREGSC.000

Note: The largest grid blocks measure 200 meters, the medium size blocks are 100 m and the smallest blocks measure 50 m. Additional information on the scale and orientation of the grid is presented in BSC 2004 [DIRS 166107], Figure C-6. The direction of x-axis is north. Units of temperature are degree Celsius. The red lines represent the repository outline.

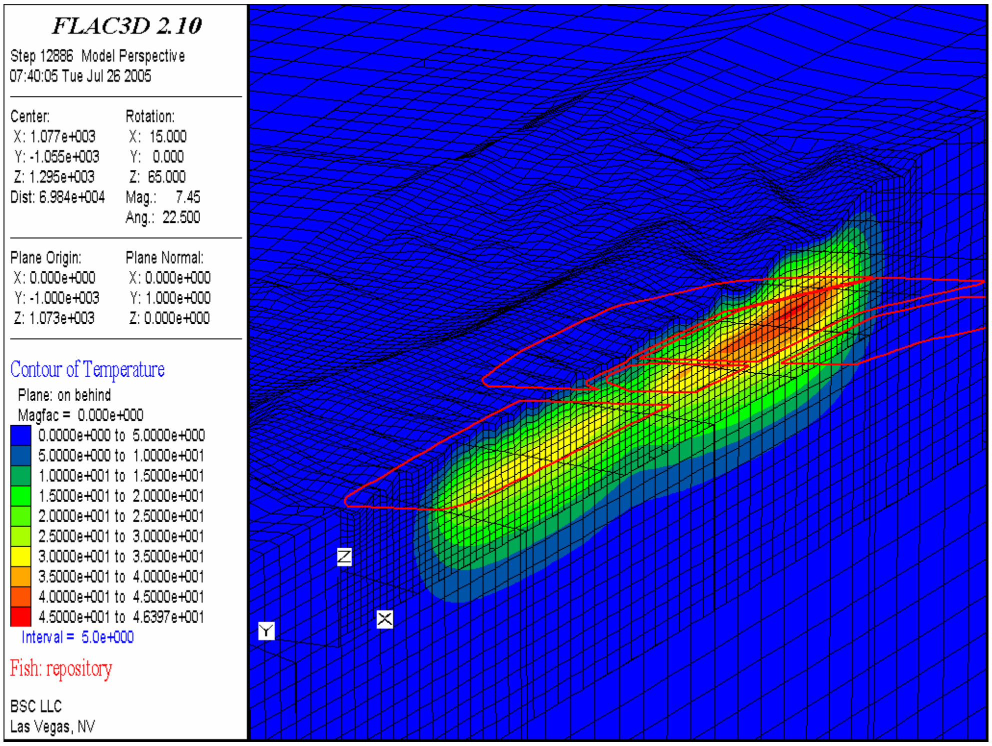
Figure C-1. Contours of Mean Temperature Change after 2000 Years of the Emplacement



Output DTN: MO0507MWDREGSC.000

Note: The largest grid blocks measure 200 meters, the medium size blocks are 100 m and the smallest blocks measure 50 m. Additional information on the scale and orientation of the grid is presented in BSC 2004 [DIRS 166107], Figure C-6. The direction of x-axis is north. Units of temperature are degree Celsius. The red lines represent the repository outline.

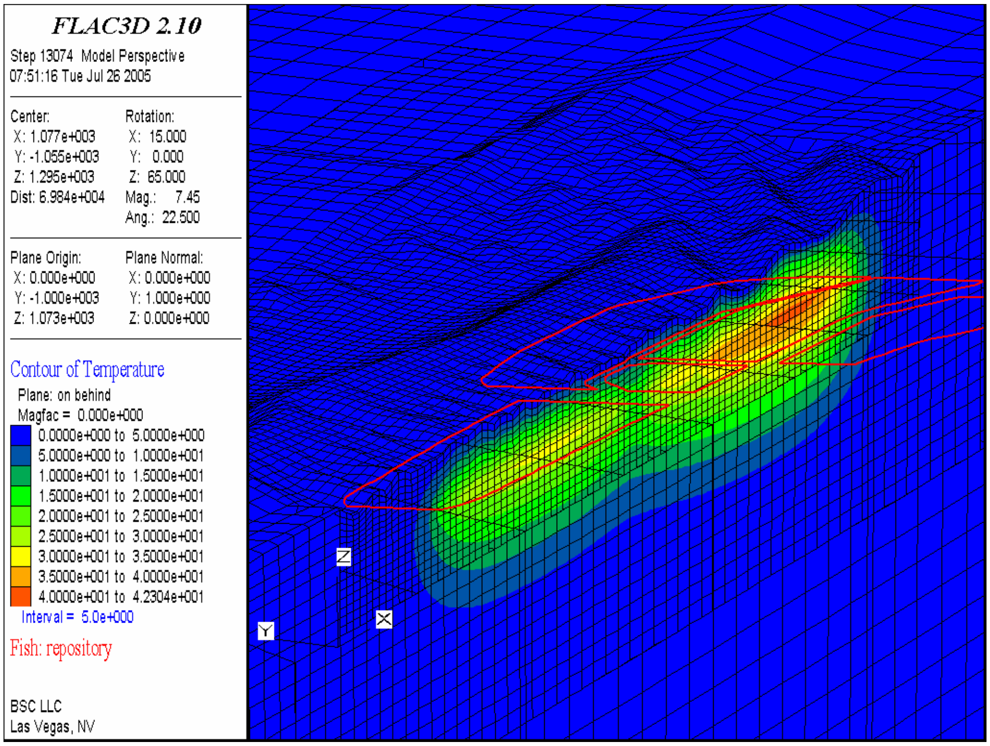
Figure C-2. Contours of Mean Temperature Change after 3000 Years of the Emplacement



Output DTN: MO0507MWDREGSC.000

Note: The largest grid blocks measure 200 meters, the medium size blocks are 100 m and the smallest blocks measure 50 m. Additional information on the scale and orientation of the grid is presented in BSC 2004 [DIRS 166107], Figure C-6. The direction of x-axis is north. Units of temperature are degree Celsius. The red lines represent the repository outline.

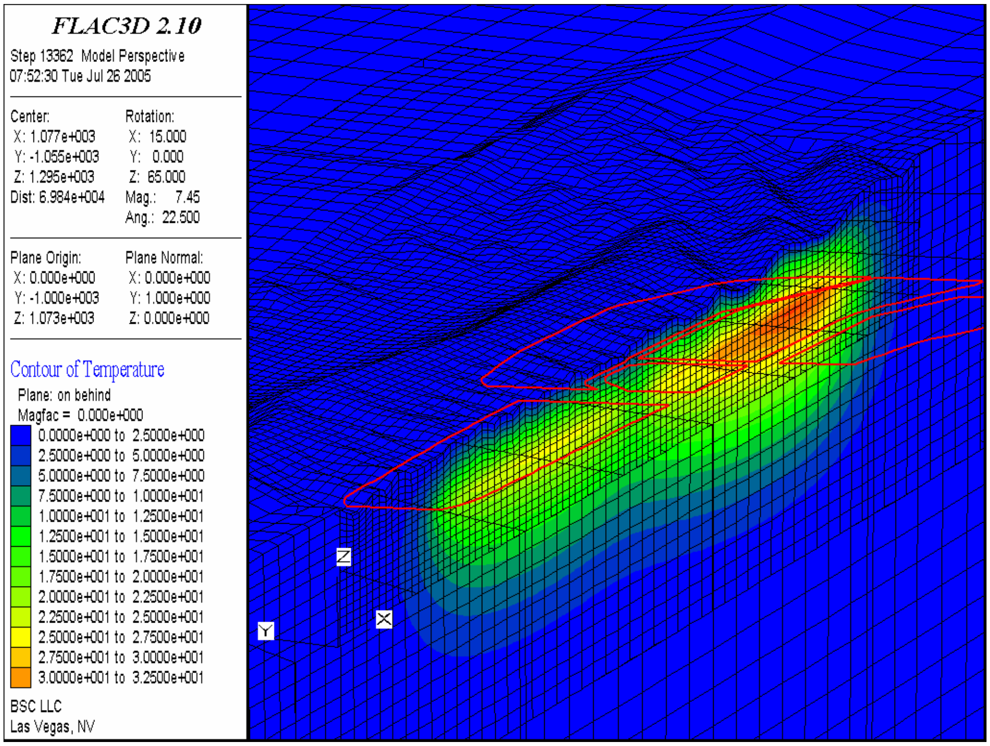
Figure C-3. Contours of Mean Temperature Change after 4000 Years of the Emplacement



Output DTN: MO0507MWDREGSC.000

Note: The largest grid blocks measure 200 meters, the medium size blocks are 100 m and the smallest blocks measure 50 m. Additional information on the scale and orientation of the grid is presented in BSC 2004 [DIRS 166107], Figure C-6. The direction of x-axis is north. Units of temperature are degree Celsius. The red lines represent the repository outline.

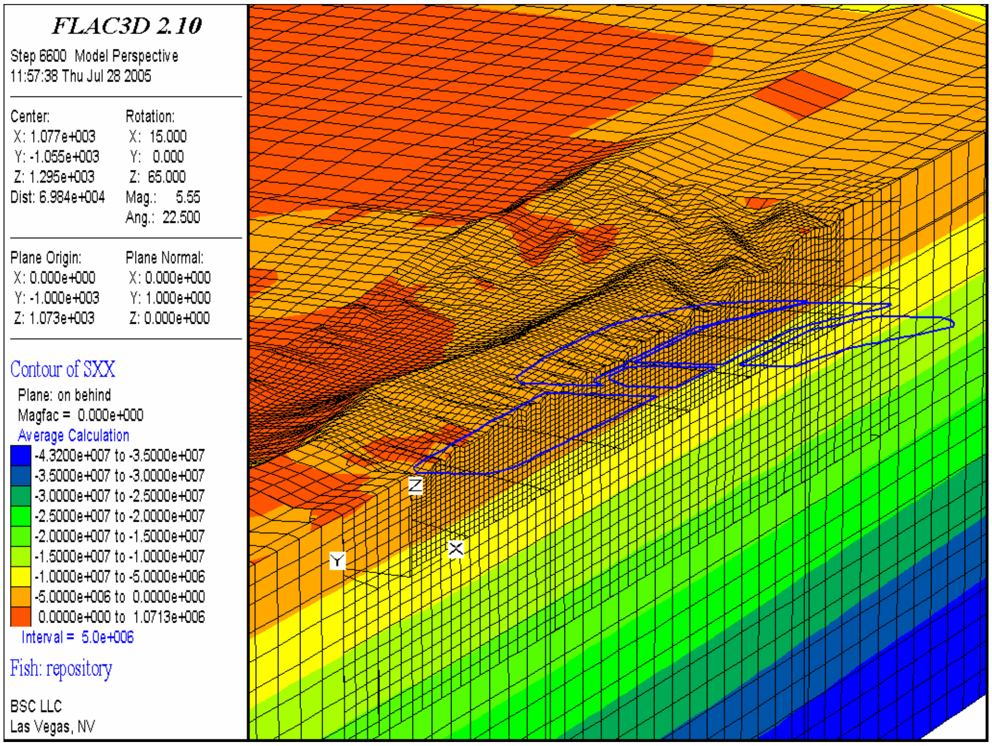
Figure C-4. Contours of Mean Temperature Change after 5000 Years of the Emplacement



Output DTN: MO0507MWDREGSC.000

Note The largest grid blocks measure 200 meters, the medium size blocks are 100 m and the smallest blocks measure 50 m. Additional information on the scale and orientation of the grid is presented in BSC 2004 [DIRS 166107], Figure C-6. The direction of x-axis is north. Units of temperature are degree Celsius. The red lines represent the repository outline.

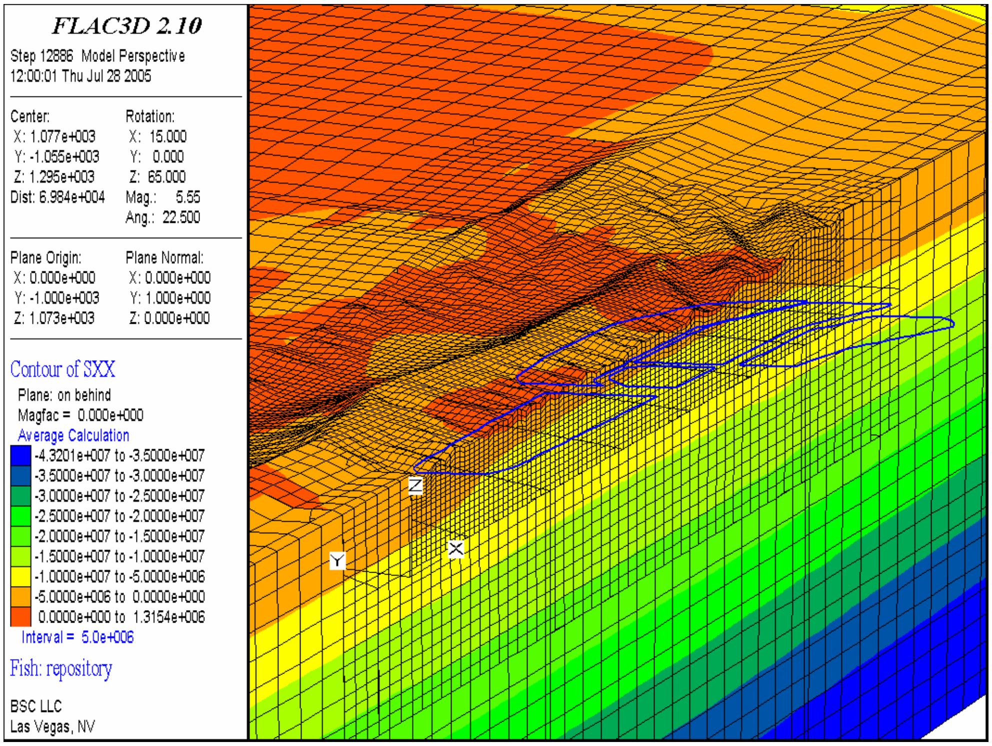
Figure C-5. Contours of Mean Temperature Change after 7500 Years of the Emplacement



Output DTN: MO0507MWDREGSC.000

Note: The largest grid blocks measure 200 meters, the medium size blocks are 100 m and the smallest blocks measure 50 m. Additional information on the scale and orientation of the grid is presented in BSC 2004 [DIRS 166107], Figure C-6. The direction of x-axis is north. Units of temperature are degree Celsius. The blue lines represent the repository outline.

Figure C-6. Contours of Induced Horizontal Stress σ_x after 0 Years of the Emplacement



Output DTN: MO0507MWDREGSC.000

Note: The largest grid blocks measure 200 meters, the medium size blocks are 100 m and the smallest blocks measure 50 m. Additional information on the scale and orientation of the grid is presented in BSC 2004 [DIRS 166107], Figure C-6. The direction of x-axis is north. Units of temperature are degree Celsius. The blue lines represent the repository outline..

Figure C-7. Contours of Induced Horizontal Stress σ_x after 4000 Years of the Emplacement